



US011274604B2

(12) **United States Patent**  
**Schwarz et al.**

(10) **Patent No.:** **US 11,274,604 B2**  
(45) **Date of Patent:** **\*Mar. 15, 2022**

(54) **BOWED ROTOR START MITIGATION IN A GAS TURBINE ENGINE USING AIRCRAFT-DERIVED PARAMETERS**

(71) Applicant: **United Technologies Corporation**, Farmington, CT (US)

(72) Inventors: **Frederick M. Schwarz**, Glastonbury, CT (US); **Amy R. Grace**, Ellington, CT (US)

(73) Assignee: **RAYTHEON TECHNOLOGIES CORPORATION**, Farmington, CT (US)

(\*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 61 days.  
  
This patent is subject to a terminal disclaimer.

(21) Appl. No.: **16/745,921**

(22) Filed: **Jan. 17, 2020**

(65) **Prior Publication Data**  
US 2020/0291860 A1 Sep. 17, 2020

**Related U.S. Application Data**

(63) Continuation of application No. 15/042,724, filed on Feb. 12, 2016, now Pat. No. 10,539,079.

(51) **Int. Cl.**  
**F01D 19/02** (2006.01)  
**F01D 25/34** (2006.01)  
(Continued)

(52) **U.S. Cl.**  
CPC ..... **F02C 7/27** (2013.01); **F01D 19/02** (2013.01); **F01D 25/24** (2013.01); **F01D 25/34** (2013.01);  
(Continued)

(58) **Field of Classification Search**  
CPC ..... F01D 19/02; F01D 25/34; F02C 7/268; F05D 2260/85; F05D 2270/114; F05D 2270/304; F05D 2270/334  
See application file for complete search history.

(56) **References Cited**  
U.S. PATENT DOCUMENTS

1,951,875 A 3/1934 Laabs  
2,617,253 A 11/1952 Fusner et al.  
(Continued)

FOREIGN PATENT DOCUMENTS

EP 1396611 3/2004  
EP 1533479 A2 5/2005  
(Continued)

OTHER PUBLICATIONS

EP Application No. 17155584 Extended European Search Report dated Jul. 6, 2017, 9 pages.

(Continued)

*Primary Examiner* — Jason H Duger  
(74) *Attorney, Agent, or Firm* — Cantor Colburn LLP

(57) **ABSTRACT**

A bowed rotor start mitigation system for a gas turbine engine of an aircraft is provided. The bowed rotor start mitigation system includes a motoring system and a controller coupled to the motoring system and an aircraft communication bus. The controller is configured to determine at least one inferred engine operating thermal parameter based on at least one aircraft-based parameter received on the aircraft communication bus, where the at least one inferred engine operating thermal parameter is based on data describing a history of the aircraft before an engine shutdown. The motoring system is controlled to drive rotation of a starting spool of the gas turbine engine below an engine (Continued)

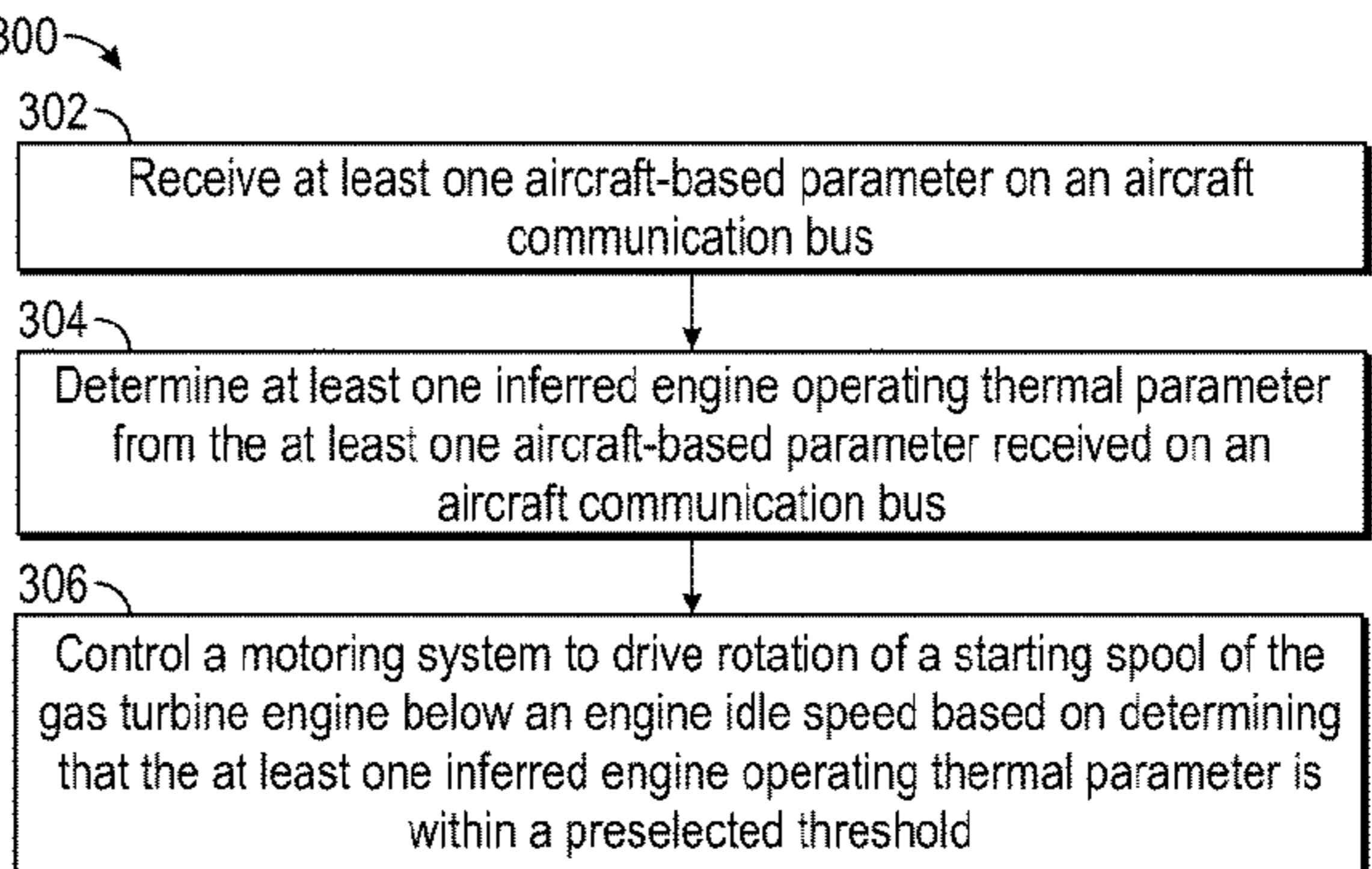
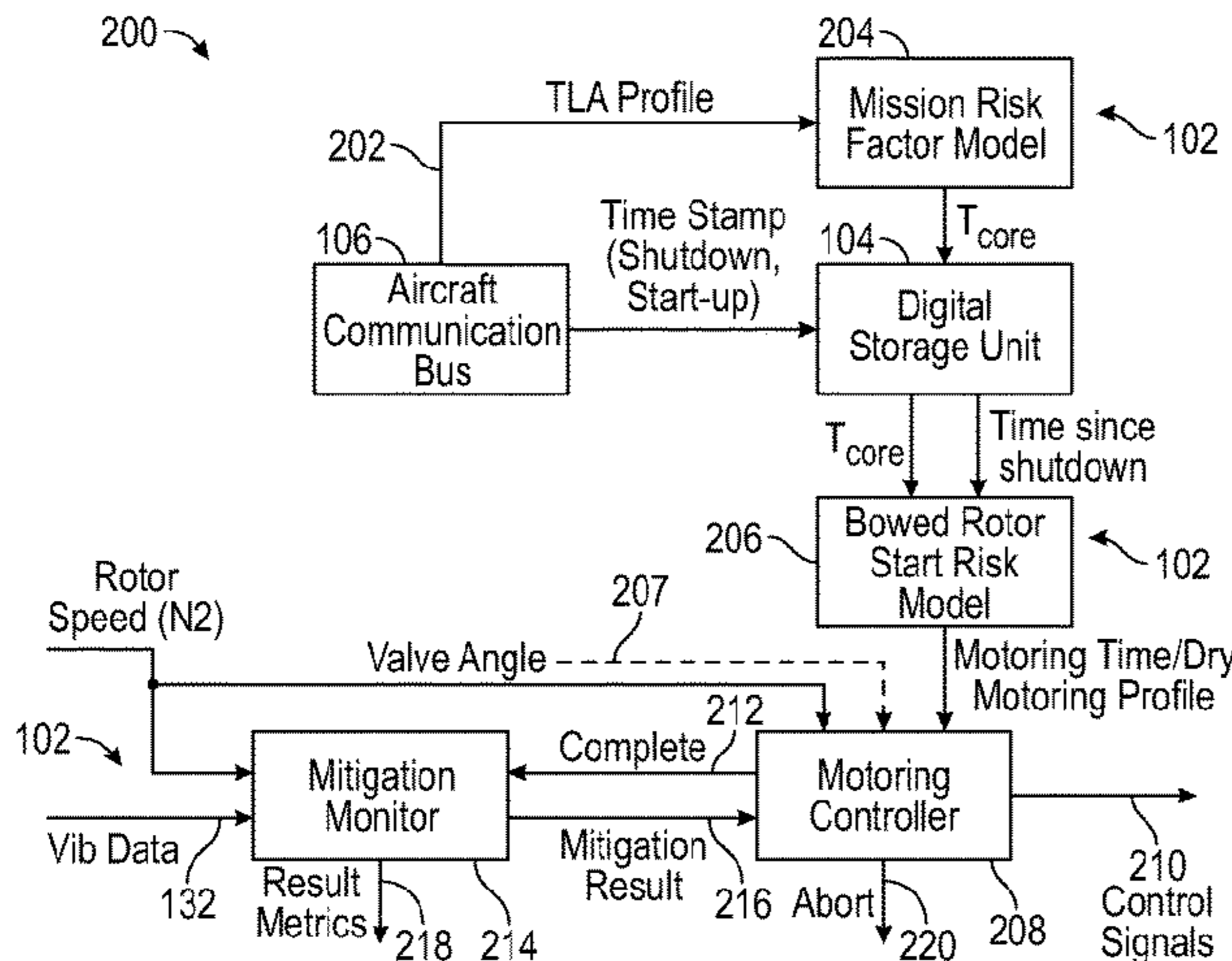


FIG. 5



idle speed based on determining that the at least one inferred engine operating thermal parameter is within a preselected range.

**20 Claims, 8 Drawing Sheets**

(51) **Int. Cl.**

- F02C 7/27* (2006.01)
- F02C 7/268* (2006.01)
- F01D 25/24* (2006.01)
- F02C 3/107* (2006.01)
- F02C 7/06* (2006.01)
- F02K 3/04* (2006.01)
- G05B 15/02* (2006.01)

(52) **U.S. Cl.**

- CPC ..... *F02C 3/107* (2013.01); *F02C 7/06* (2013.01); *F02C 7/268* (2013.01); *F02K 3/04* (2013.01); *G05B 15/02* (2013.01); *F05D 2220/323* (2013.01); *F05D 2260/85* (2013.01); *F05D 2270/021* (2013.01); *F05D 2270/114* (2013.01); *F05D 2270/304* (2013.01); *F05D 2270/334* (2013.01)

(56)

**References Cited**

U.S. PATENT DOCUMENTS

2,962,597	A	11/1960	Evans
3,057,155	A	10/1962	Rizk
3,151,452	A	10/1964	Bunger et al.
3,290,709	A	12/1966	Whitenack, Jr. et al.
3,360,844	A	1/1968	Wonneman
3,764,815	A	10/1973	Habock et al.
3,793,905	A	2/1974	Black et al.
3,898,439	A	8/1975	Reed et al.
3,951,008	A	4/1976	Schneider et al.
4,044,550	A	8/1977	Vermilye
4,069,424	A	1/1978	Burkett
4,120,159	A	10/1978	Matsumoto et al.
4,144,421	A	3/1979	Sakai
4,302,813	A	11/1981	Kurihara et al.
4,353,604	A	10/1982	Dulberger et al.
4,380,146	A	4/1983	Yannone et al.
4,426,641	A	1/1984	Kurihara et al.
4,435,770	A	3/1984	Shiohata et al.
4,437,163	A	3/1984	Kurihara et al.
4,453,407	A	6/1984	Sato et al.
4,485,678	A	12/1984	Fanuele
4,488,240	A	12/1984	Kapadia et al.
4,496,252	A	1/1985	Horler et al.
4,598,551	A	7/1986	Dimitroff, Jr. et al.
4,627,234	A	12/1986	Schuh
4,642,782	A	2/1987	Kemper et al.
4,669,893	A	6/1987	Chalaire et al.
4,713,985	A	12/1987	Ando
4,733,529	A	3/1988	Nelson et al.
4,747,270	A	5/1988	Klie et al.
4,854,120	A	8/1989	Nelson et al.
4,856,272	A	8/1989	Putman et al.
4,862,009	A	8/1989	King
4,979,362	A	12/1990	Vershure, Jr.
5,103,629	A	4/1992	Mumford et al.
5,123,239	A	6/1992	Rodgers
5,127,220	A	7/1992	Jesrai et al.
5,174,109	A	12/1992	Lampe
5,184,458	A	2/1993	Lampe et al.
5,201,798	A	4/1993	Hogan
5,349,814	A	9/1994	Ciokajlo et al.
5,388,960	A	2/1995	Suzuki et al.
6,146,090	A	11/2000	Schmidt
6,168,377	B1	1/2001	Wolfe et al.
6,190,127	B1	2/2001	Schmidt

6,318,958	B1	11/2001	Giesler et al.
6,478,534	B2	11/2002	Bangert et al.
6,498,978	B2	12/2002	Leamy et al.
6,517,314	B1	2/2003	Burnett et al.
6,558,118	B1	5/2003	Brisson et al.
6,681,579	B2	1/2004	Lane et al.
6,762,512	B2	7/2004	Nelson
7,104,072	B2	9/2006	Thompson
7,133,801	B2	11/2006	Song
7,409,319	B2	8/2008	Kant et al.
7,428,819	B2	9/2008	Cataldi et al.
7,507,070	B2	3/2009	Jones
7,543,439	B2	6/2009	Butt et al.
7,587,133	B2	9/2009	Franke et al.
7,742,881	B2	6/2010	Muralidharan et al.
7,798,720	B1	9/2010	Walsh
7,909,566	B1	3/2011	Brostmeyer
7,972,105	B2	7/2011	Dejoris et al.
8,090,456	B2	1/2012	Karpman et al.
8,291,715	B2	10/2012	Libera et al.
8,306,776	B2	11/2012	Ihara et al.
8,770,913	B1	7/2014	Negron et al.
8,776,530	B2	7/2014	Shirooni et al.
8,820,046	B2	9/2014	Ross et al.
8,918,264	B2	12/2014	Jegu et al.
9,086,018	B2	7/2015	Winston et al.
9,121,309	B2	9/2015	Geiger
9,429,510	B2	8/2016	Belsom et al.
9,664,070	B1	5/2017	Clauson et al.
9,699,833	B2	7/2017	Broughton et al.
9,845,730	B2	12/2017	Betti et al.
9,970,328	B2	5/2018	Haerms et al.
9,988,928	B2	6/2018	Popescu et al.
10,040,577	B2	8/2018	Teicholz et al.
2002/0173897	A1	11/2002	Leamy et al.
2003/0145603	A1	8/2003	Reed et al.
2003/0209910	A1*	11/2003	Nelson ..... F02C 7/268 290/52
2004/0065091	A1	4/2004	Anderson
2004/0131138	A1	7/2004	Correia et al.
2006/0032234	A1	2/2006	Thompson
2006/0188372	A1	8/2006	Hansen
2006/0260323	A1	11/2006	Moulebar
2007/0031249	A1	2/2007	Jones
2007/0151258	A1	7/2007	Gaines et al.
2008/0072568	A1	3/2008	Moniz et al.
2009/0246018	A1	10/2009	Kondo et al.
2009/0301053	A1	12/2009	Geiger
2009/0314002	A1	12/2009	Libera et al.
2010/0095791	A1	4/2010	Galloway
2010/0132365	A1	6/2010	Labala
2010/0293961	A1	11/2010	Tong et al.
2010/0326085	A1	12/2010	Veilleux
2011/0077783	A1	3/2011	Karpman et al.
2011/0146276	A1	6/2011	Sathyanarayana et al.
2011/0153295	A1	6/2011	Yerramalla et al.
2011/0289936	A1	12/2011	Suciu et al.
2011/0296843	A1	12/2011	Lawson, Jr.
2011/0308345	A1	12/2011	Makulec et al.
2012/0031067	A1	2/2012	Sundaram et al.
2012/0121373	A1	5/2012	Short et al.
2012/0240591	A1	9/2012	Snider et al.
2012/0266601	A1	10/2012	Miller
2012/0297781	A1	11/2012	Manchikanti et al.
2012/0316748	A1	12/2012	Jegu et al.
2013/0031912	A1	2/2013	Finney et al.
2013/0091850	A1	4/2013	Francisco
2013/0101391	A1	4/2013	Szwedowicz et al.
2013/0134719	A1	5/2013	Watanabe et al.
2013/0251501	A1	9/2013	Araki et al.
2014/0060076	A1	3/2014	Cortelli et al.
2014/0123673	A1	5/2014	Mouze et al.
2014/0199157	A1	7/2014	Haerms et al.
2014/0236451	A1	8/2014	Gerez et al.
2014/0241878	A1	8/2014	Herrig et al.
2014/0271152	A1	9/2014	Rodriguez
2014/0301820	A1	10/2014	Lohse et al.
2014/0318144	A1	10/2014	Lazzeri et al.

(56)

References Cited

U.S. PATENT DOCUMENTS

2014/0321981 A1\* 10/2014 Rodriguez ..... F01D 25/26  
415/116

2014/0334927 A1 11/2014 Hammerum

2014/0366546 A1 12/2014 Bruno et al.

2014/0373518 A1 12/2014 Manneville et al.

2014/0373552 A1\* 12/2014 Zaccaria ..... F02C 7/277  
60/778

2014/0373553 A1 12/2014 Zaccaria et al.

2014/0373554 A1 12/2014 Pech et al.

2015/0016949 A1 1/2015 Smith

2015/0115608 A1 4/2015 Draper

2015/0121874 A1 5/2015 Yoshida et al.

2015/0128592 A1 5/2015 Filiputti et al.

2015/0159625 A1 6/2015 Hawdwicke, Jr. et al.

2015/0219121 A1 8/2015 King

2015/0377141 A1 12/2015 Foiret

2016/0236369 A1 8/2016 Baker

2016/0245312 A1 8/2016 Morice

2016/0265387 A1 9/2016 Duong et al.

2016/0288325 A1 10/2016 Naderer et al.

2017/0030265 A1 2/2017 O'Toole et al.

2017/0218848 A1 8/2017 Alstad et al.

2017/0233103 A1 8/2017 Teicholz et al.

2017/0234158 A1 8/2017 Savela

2017/0234166 A1 8/2017 Dube et al.

2017/0234167 A1 8/2017 Stachowiak et al.

2017/0234230 A1 8/2017 Schwarz et al.

2017/0234231 A1 8/2017 Virtue, Jr. et al.

2017/0234232 A1 8/2017 Sheridan et al.

2017/0234233 A1 8/2017 Schwarz et al.

2017/0234235 A1 8/2017 Pech

2017/0234236 A1 8/2017 Feulner et al.

2017/0234238 A1 8/2017 Schwarz et al.

2017/0236064 A1 8/2017 Kirschnick

2017/0274390 A1 9/2017 Manyapu et al.

2018/0010480 A1 1/2018 Hockaday et al.

2018/0265223 A1 9/2018 Teicholz et al.

2018/0274390 A1 9/2018 Clauson et al.

2018/0327117 A1 11/2018 Teicholz et al.

FOREIGN PATENT DOCUMENTS

EP 1862875 12/2007

EP 2006496 12/2008

EP 2305986 A2 4/2011

EP 2363575 A2 9/2011

EP 2871333 5/2015

EP 3051074 8/2016

FR 2933131 1/2010

GB 1374810 11/1974

GB 2117842 10/1983

GB 2218751 11/1989

IN 201408865 5/2015

JP 2002371806 12/2002

JP 2004036414 2/2004

WO 9900585 1/1999

WO 2013007912 1/2013

WO 2014152701 A1 9/2014

WO 2015030946 3/2015

WO 2016069303 5/2016

OTHER PUBLICATIONS

EP Application No. 17155601 Extended European Search Report dated Jun. 30, 2017, 7 pages.

EP Application No. 17155612 Extended European Search Report dated Jul. 4, 2017, 8 pages.

EP Application No. 17155612.9 Office Action dated Oct. 2, 2018, 3 pages.

EP Application No. 17155613 Extended European Search Report dated Jun. 27, 2017, 10 pages.

EP Application No. 17155683 Extended European Search Report dated Jun. 30, 2017, 8 pages.

EP Application No. 17155683 Office Action dated May 22, 2018, 2 pages.

EP Application No. 17155687 Extended European Search Report dated Jun. 16, 2017, 9 pages.

EP Application No. 17155698 Extended European Search Report dated Jun. 21, 2017, 9 pages.

EP Application No. 17155698.8 Office Action dated Sep. 27, 2018, 3 pages.

EP Application No. 17155698.8 Office Action dated Jul. 17, 2019, 4 pages.

EP Application No. 17155721 Extended European Search Report dated Jun. 27, 2017, 8 pages.

EP Application No. 17155793 Extended European Search Report dated Jun. 30, 2017, 10 pages.

EP Application No. 17155798 Extended European Search Report dated Jun. 30, 2017, 9 pages.

EP Application No. 17155798.6 Office Action dated Sep. 21, 2018, 3 pages.

EP Application No. 17155807 Extended European Search Report dated Jul. 3, 2017, 8 pages.

Extended European Search Report for Application No. 17179407. 6-1610 dated Dec. 5, 2017, 8 pages.

EP Application No. 20164205.5 Extended EP Search Report dated May 27, 2020, 8 pages.

EP Application No. 17155698.8 Office Action dated Apr. 22, 2021, 6 pages.

\* cited by examiner



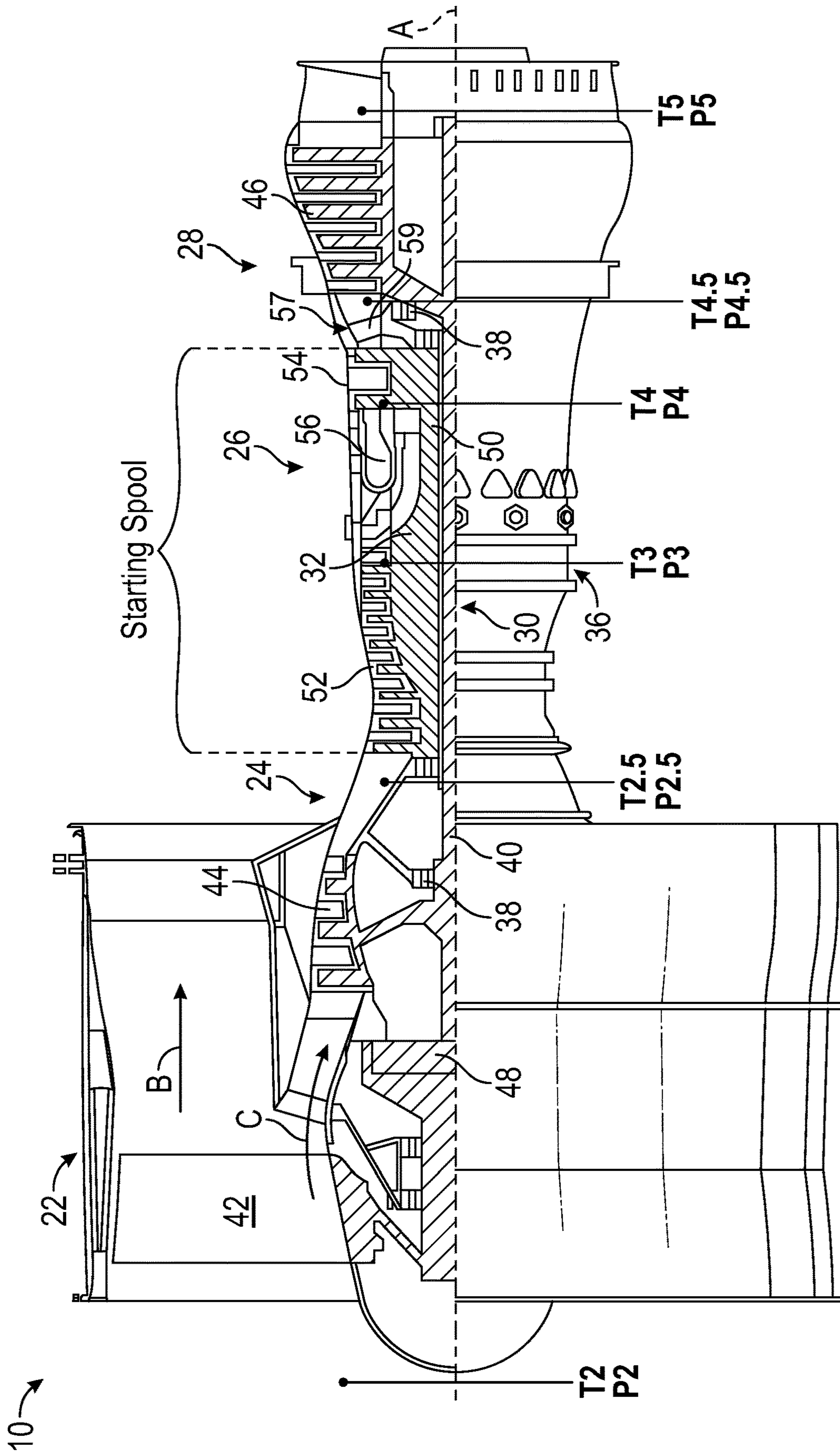


FIG. 1

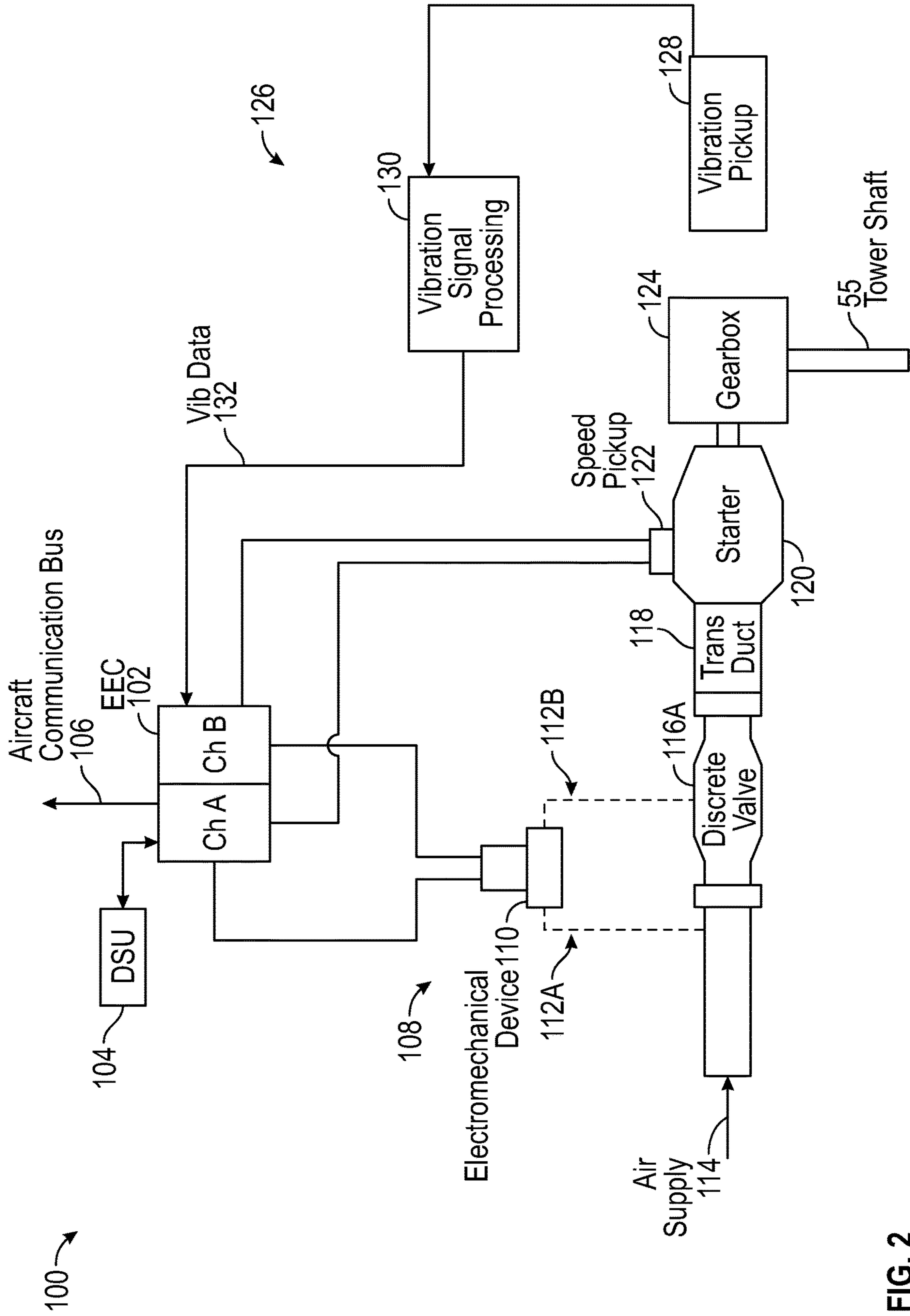


FIG. 2

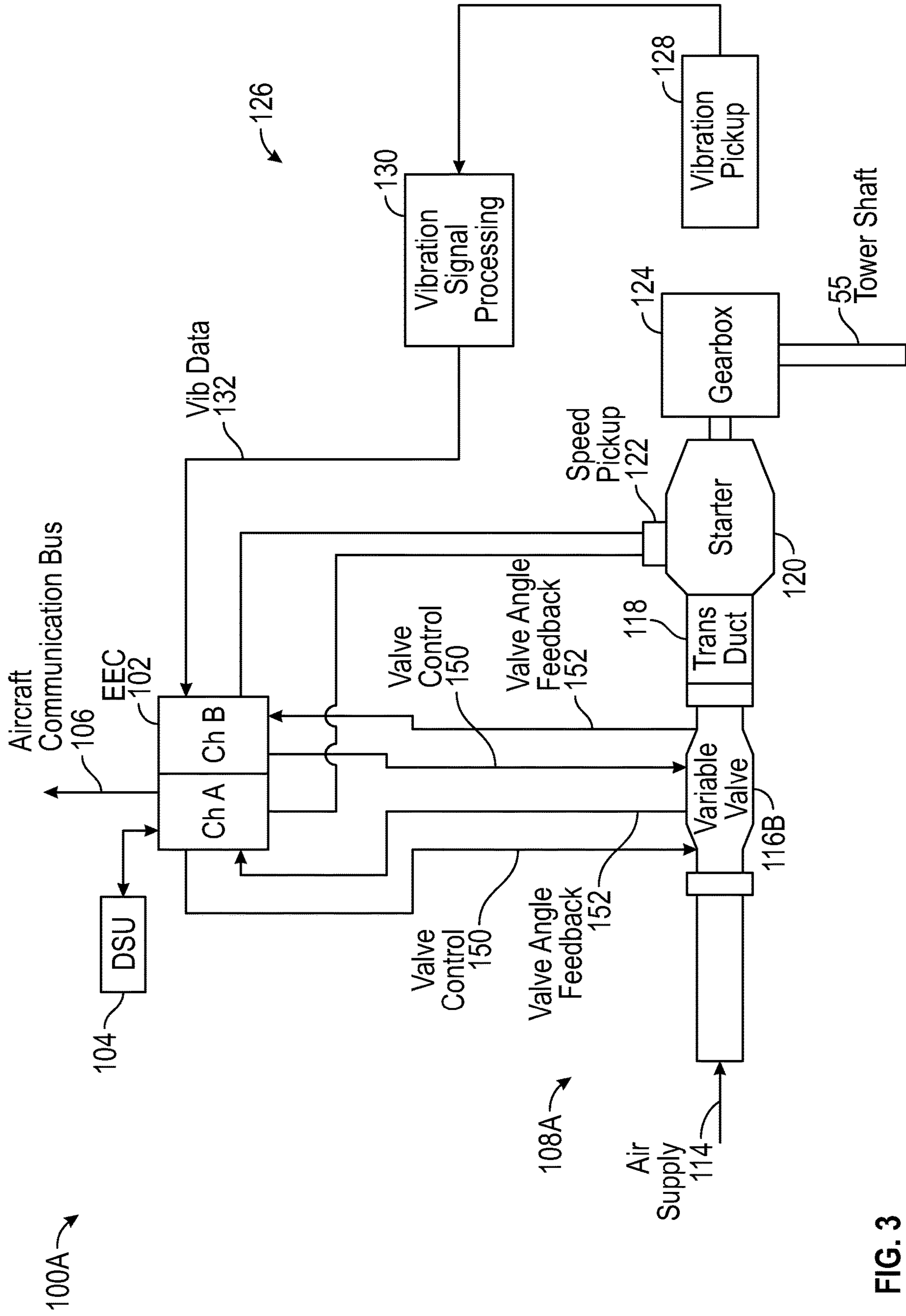


FIG. 3

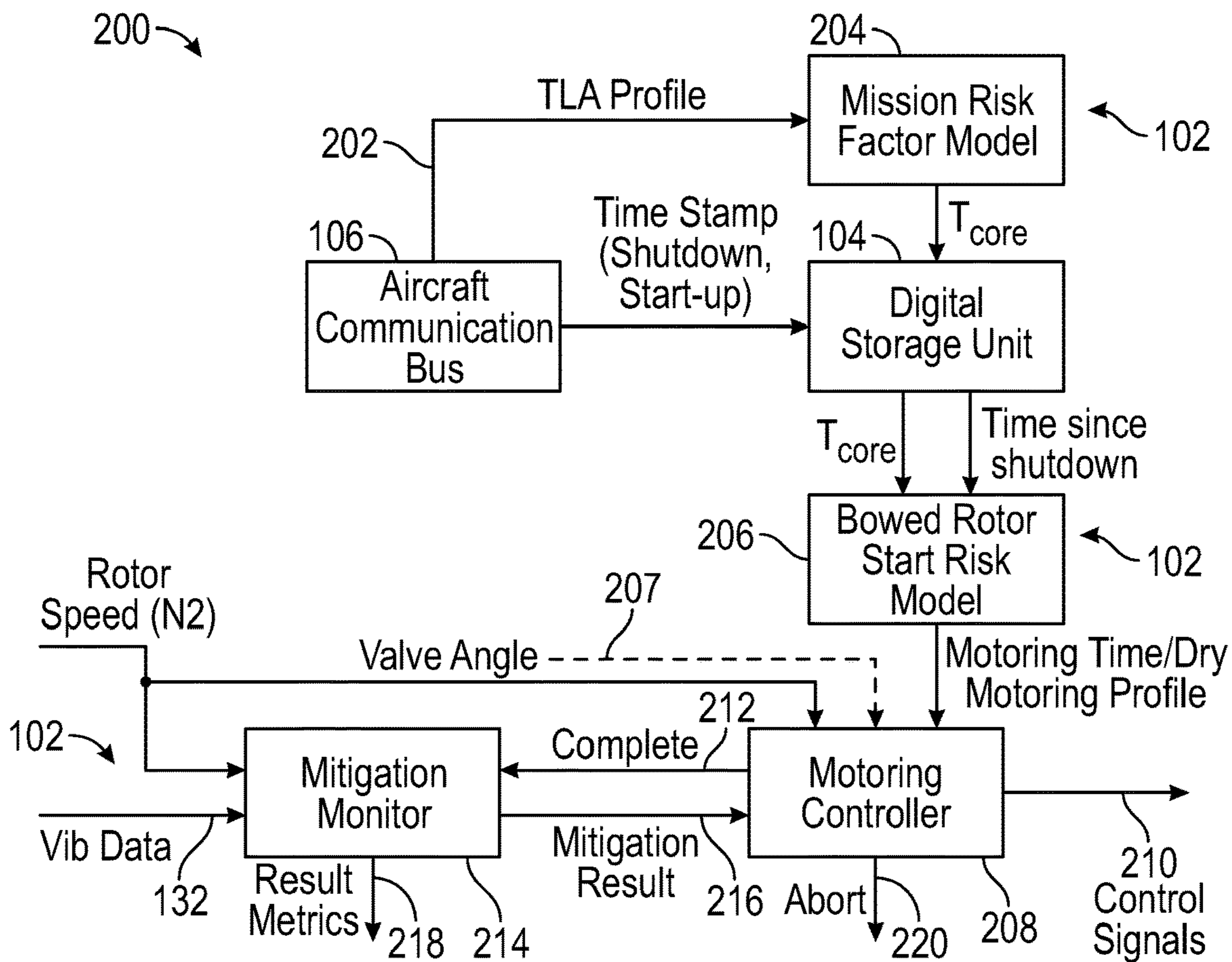


FIG. 4

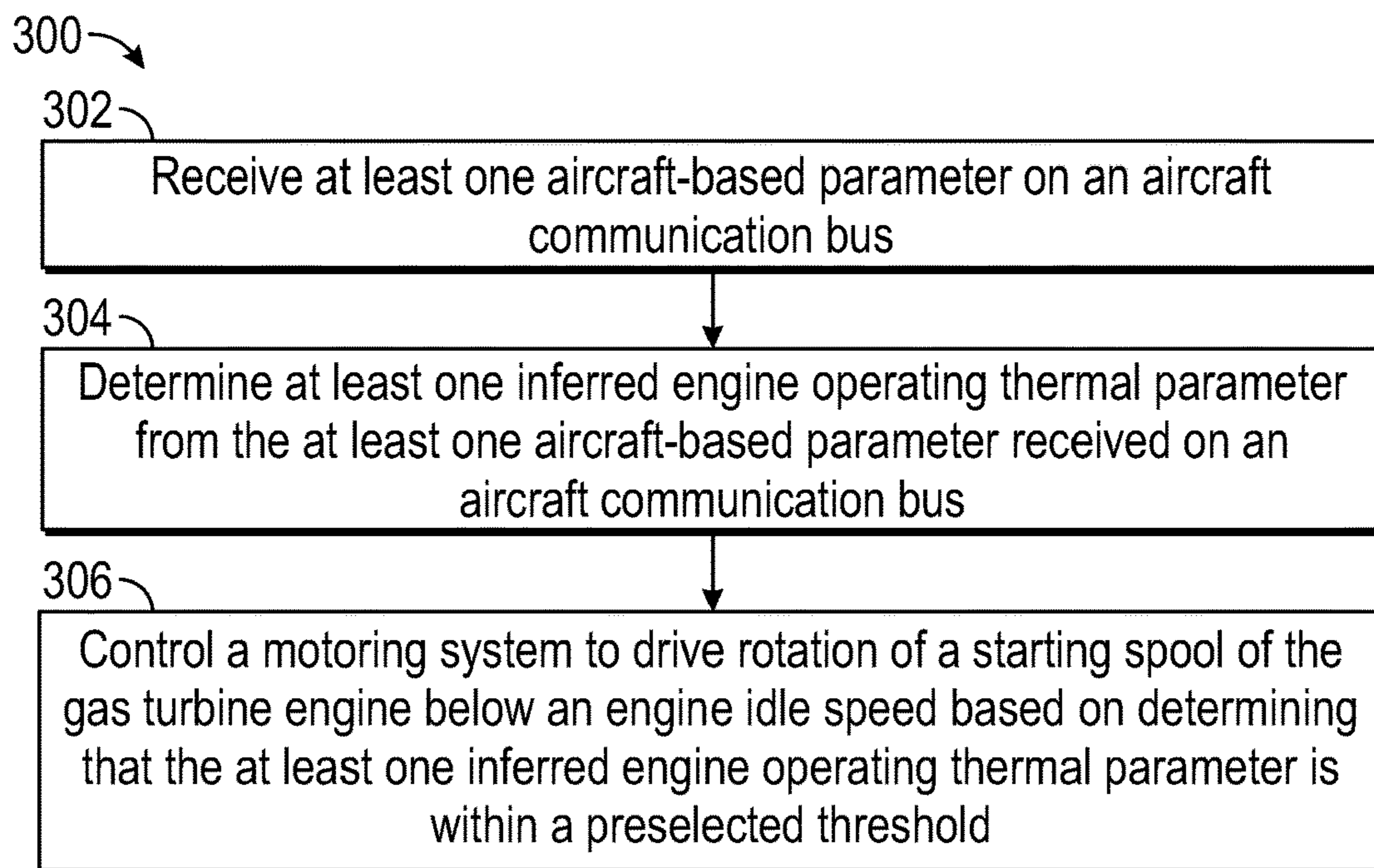


FIG. 5



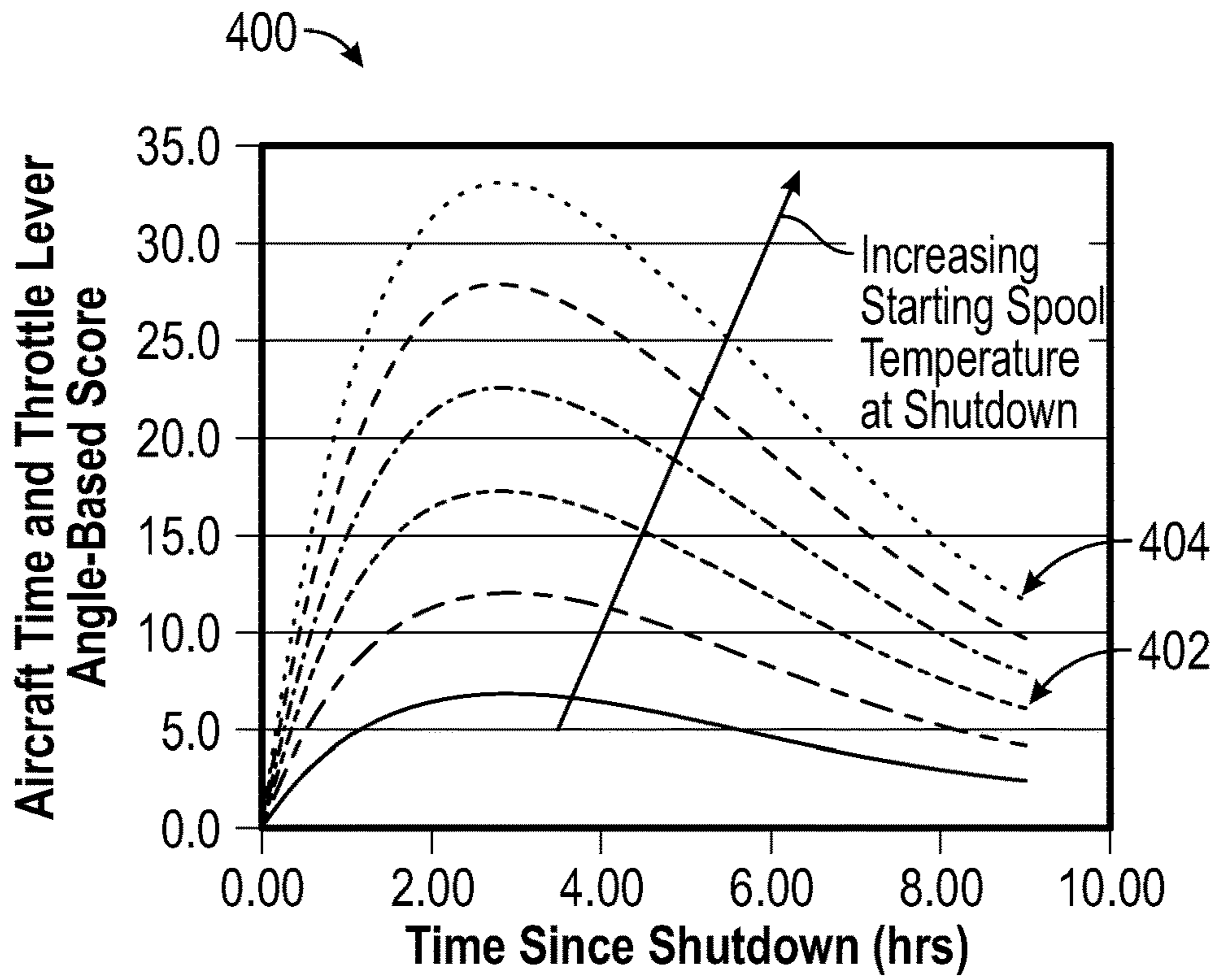


FIG. 6

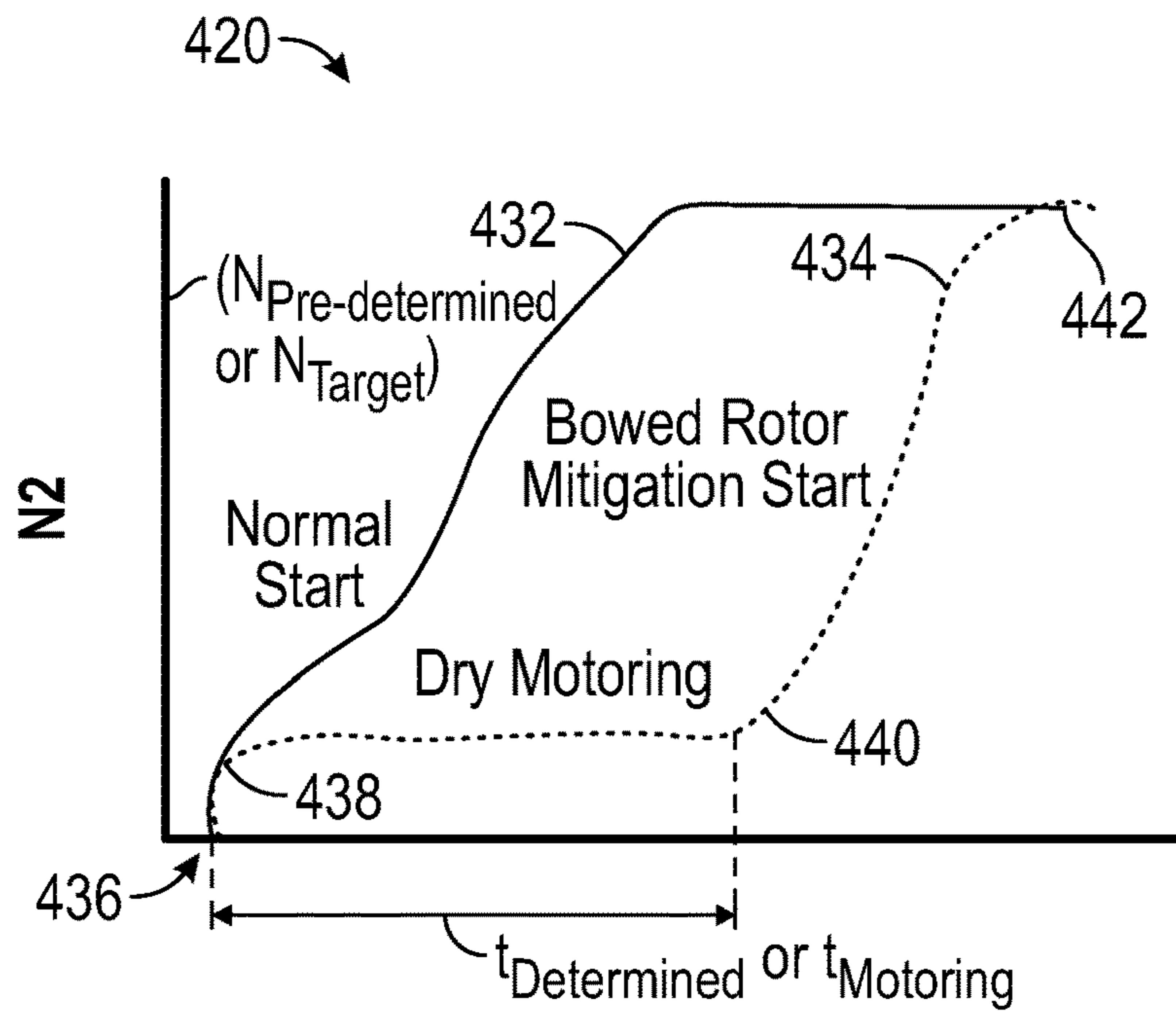


FIG. 7



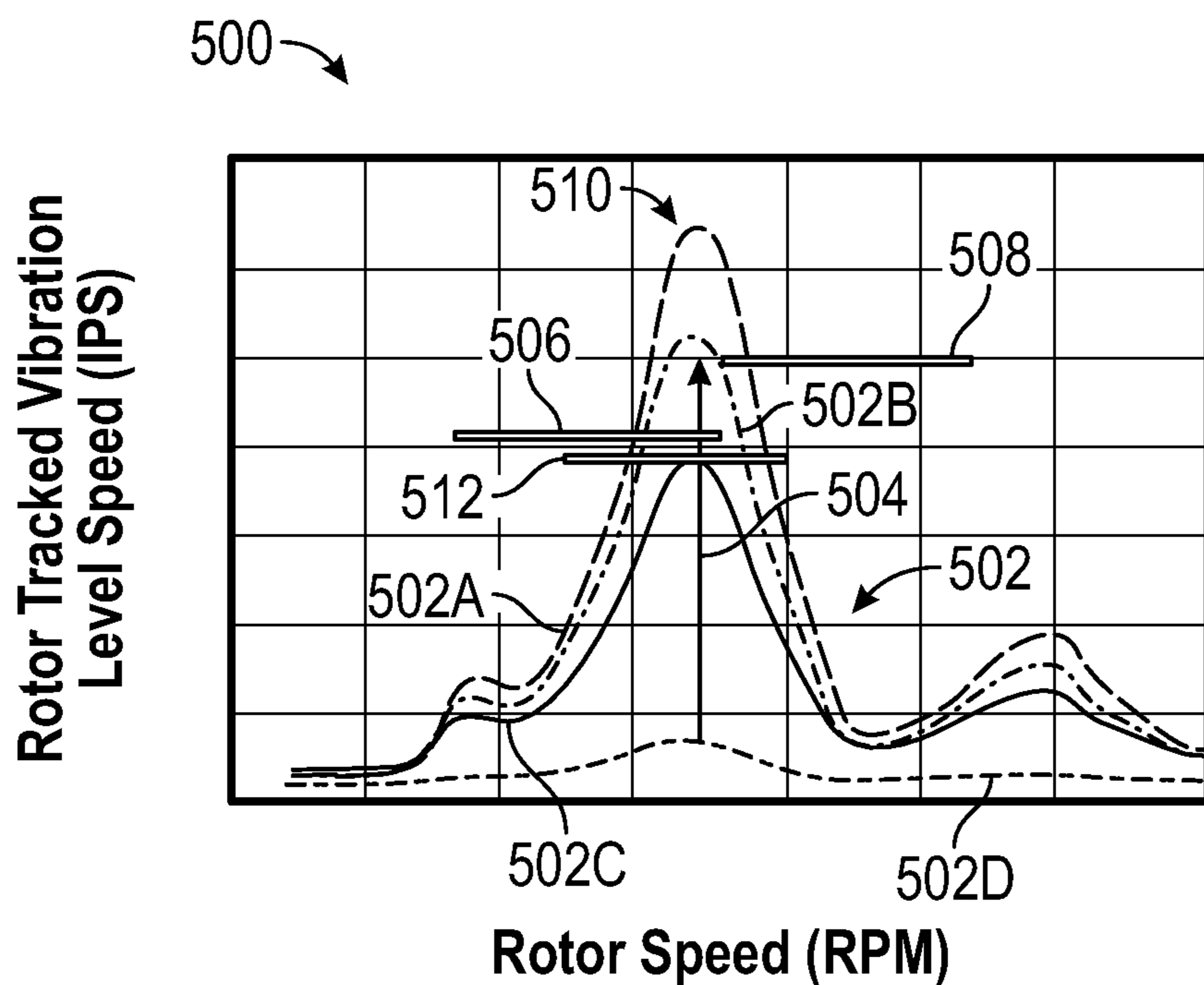


FIG. 8

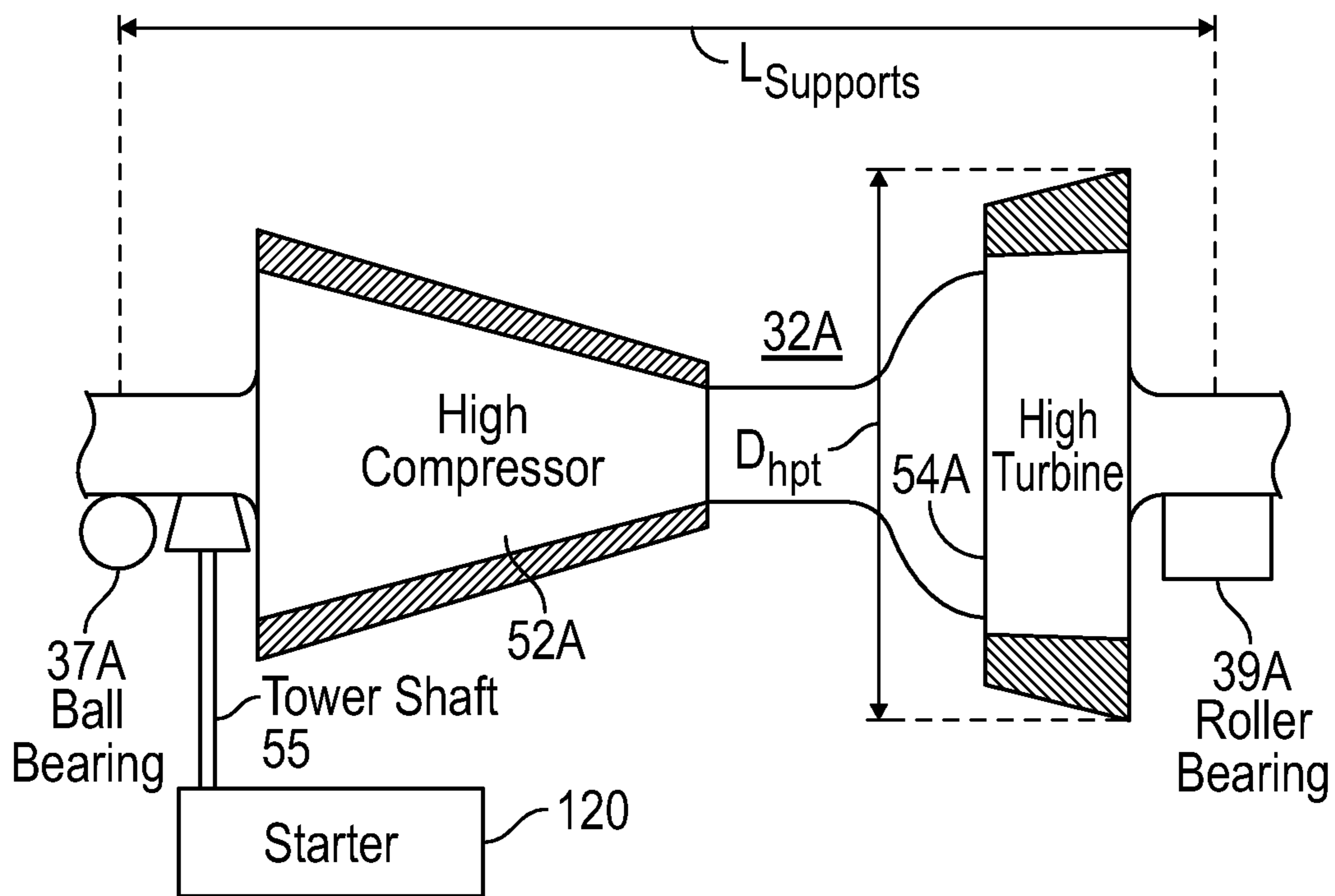


FIG. 9

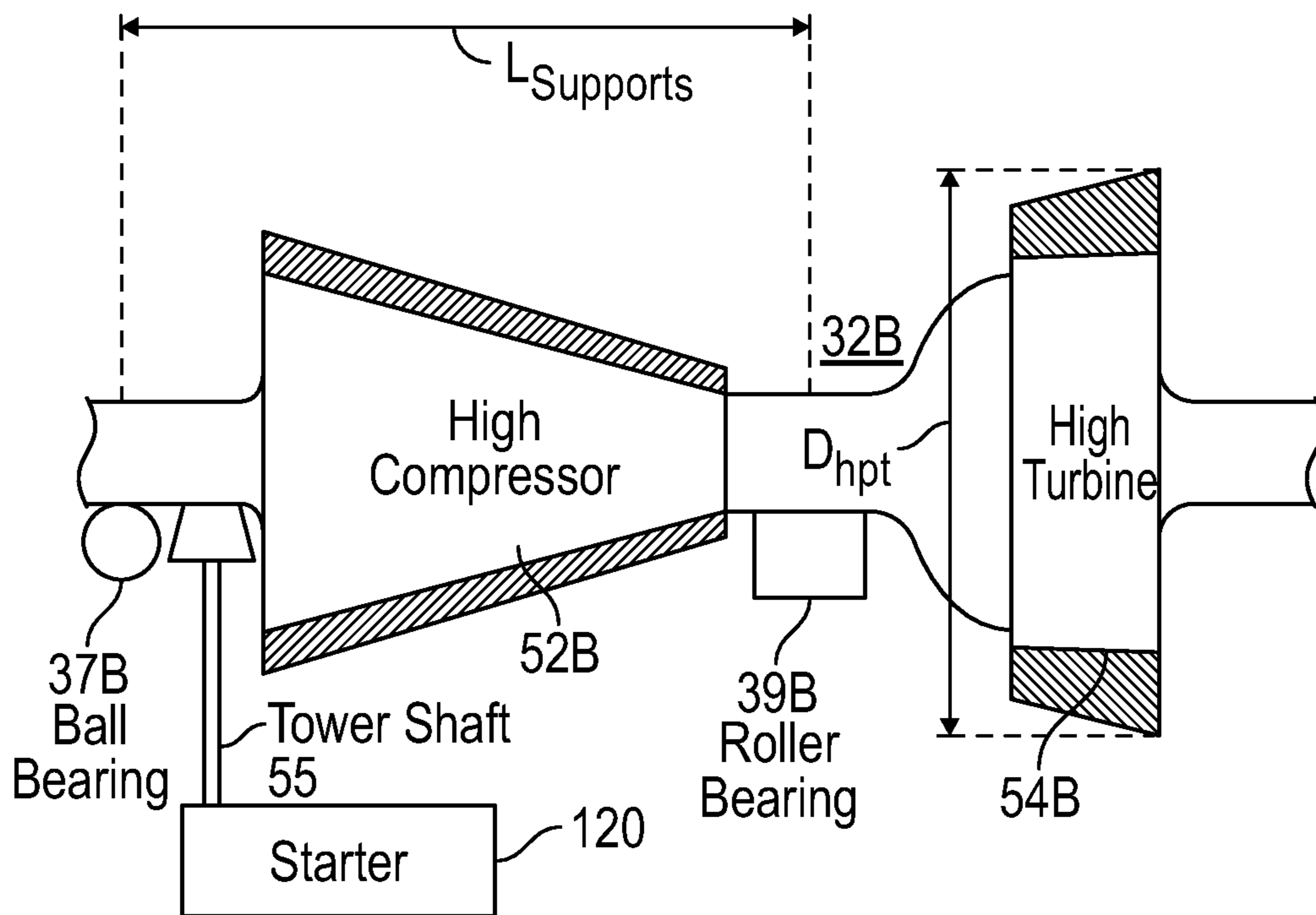


FIG. 10

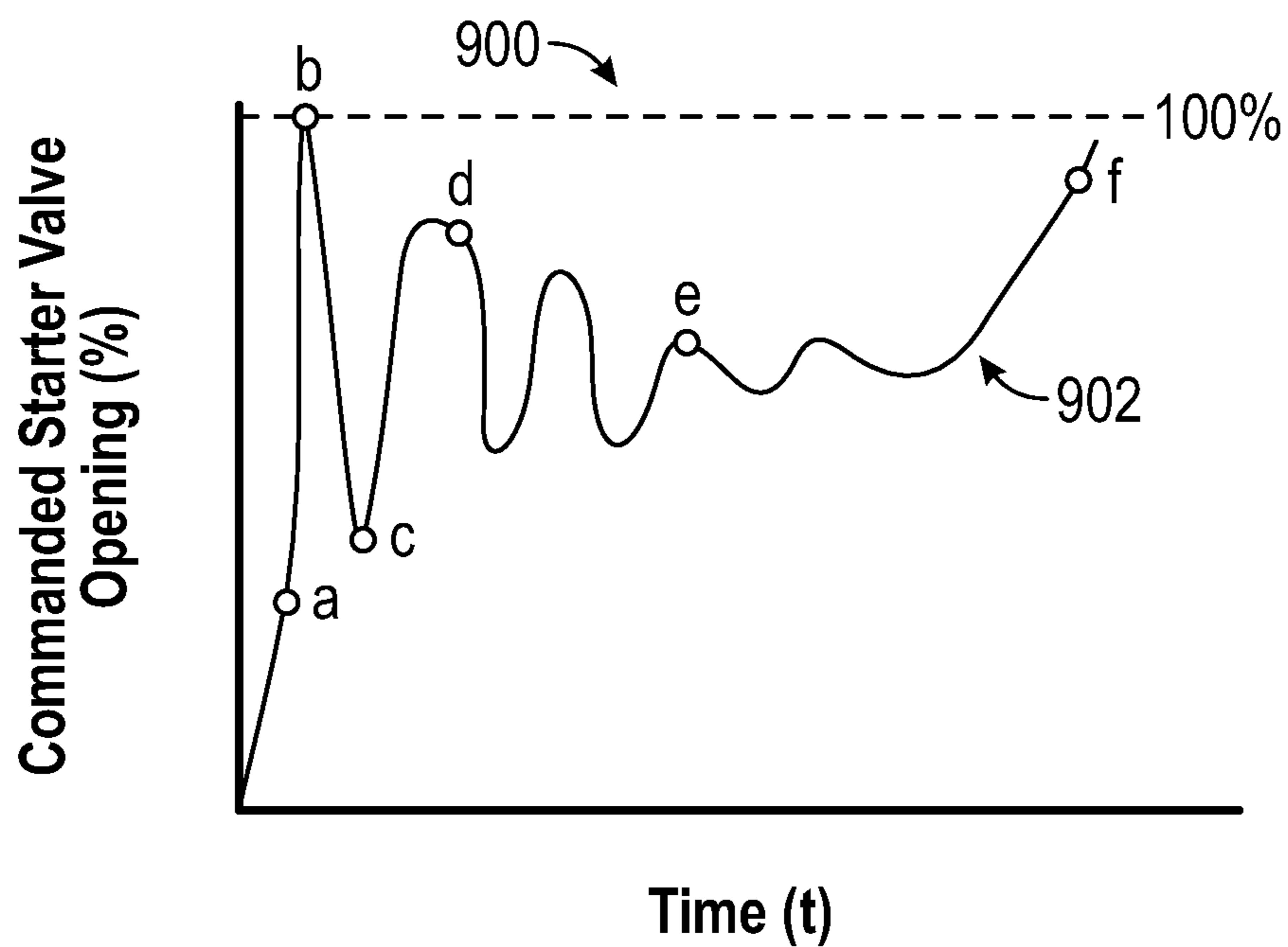


FIG. 11





**BOWED ROTOR START MITIGATION IN A  
GAS TURBINE ENGINE USING  
AIRCRAFT-DERIVED PARAMETERS**

CROSS-REFERENCE TO RELATED  
APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 15/042,724 filed Feb. 12, 2016, the disclosure of which is incorporated by reference herein in its entirety.

BACKGROUND

This disclosure relates to gas turbine engines, and more particularly to an apparatus, system and method for mitigating a bowed rotor start condition in a gas turbine engine using aircraft-derived parameters.

Gas turbine engines are used in numerous applications one of which is for providing thrust to an airplane. When the gas turbine engine of an airplane has been shut off for example, after an airplane has landed at an airport, the engine is hot and due to heat rise, the upper portions of the engine will be hotter than lower portions of the engine. When this occurs thermal expansion may cause deflection of components of the engine which may result in a “bowed rotor” condition. If a gas turbine engine is in such a “bowed rotor” condition it is undesirable to restart or start the engine.

Accordingly, it is desirable to provide a method and/or apparatus for detecting and preventing a “bowed rotor” condition.

BRIEF DESCRIPTION

In an embodiment, a bowed rotor start mitigation system for a gas turbine engine of an aircraft is provided. The bowed rotor start mitigation system includes a motoring system and a controller coupled to the motoring system and an aircraft communication bus. The controller is configured to determine at least one inferred engine operating thermal parameter based on at least one aircraft-based parameter received on the aircraft communication bus, where the at least one inferred engine operating thermal parameter is based on data describing a history of the aircraft before an engine shutdown. The motoring system is controlled to drive rotation of a starting spool of the gas turbine engine below an engine idle speed based on determining that the at least one inferred engine operating thermal parameter is within a preselected range.

In addition to one or more of the features described above, or as an alternative to any of the foregoing embodiments, further embodiments may include where the at least one aircraft-based parameter is indicative of a history of fuel demand for the aircraft.

In addition to one or more of the features described above, or as an alternative to any of the foregoing embodiments, further embodiments may include where a time since the engine shutdown is used to modify a time of rotation of the starting spool by the motoring system.

In addition to one or more of the features described above, or as an alternative to any of the foregoing embodiments, further embodiments may include where the controller transmits a notification on the aircraft communication bus based on the gas turbine engine being conditioned for starting.

In addition to one or more of the features described above, or as an alternative to any of the foregoing embodiments,

further embodiments may include where the controller is configured to abort rotation by the motoring system when a safety condition is detected.

In addition to one or more of the features described above, or as an alternative to any of the foregoing embodiments, further embodiments may include where the motoring system is configured to apply a braking torque to the starting spool to abort rotation of the starting spool.

In addition to one or more of the features described above, or as an alternative to any of the foregoing embodiments, further embodiments may include a rotation sensor for detecting rotary motion of the starting spool, and the controller is further coupled to the rotation sensor.

In addition to one or more of the features described above, or as an alternative to any of the foregoing embodiments, further embodiments may include where the controller is configured to remove power from the motoring system based on detecting rotary motion of the starting spool above a target speed.

In addition to one or more of the features described above, or as an alternative to any of the foregoing embodiments, further embodiments may include where a vibration monitor is used to set a maintenance flag based on detecting a vibration level that exceeds a maintenance action threshold while accelerating the starting spool of the gas turbine engine.

In addition to one or more of the features described above, or as an alternative to any of the foregoing embodiments, further embodiments may include where the at least one inferred engine operating thermal parameter includes an engine temperature value, and the at least one aircraft-based parameter received on the aircraft communication bus includes a throttle lever angle profile.

According to an embodiment, a method of bowed rotor start mitigation for a gas turbine engine of an aircraft is provided. The method includes determining at least one inferred engine operating thermal parameter based on at least one aircraft-based parameter received on an aircraft communication bus, where the at least one inferred engine operating thermal parameter is based on data describing a history of the aircraft before an engine shutdown. The method also includes controlling a motoring system to drive rotation of a starting spool of the gas turbine engine below an engine idle speed based on determining that the at least one inferred engine operating thermal parameter is within a preselected range.

A technical effect of the apparatus, systems and methods is achieved by using a start sequence for a gas turbine engine as described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

The subject matter which is regarded as the present disclosure is particularly pointed out and distinctly claimed in the claims at the conclusion of the specification. The foregoing and other features, and advantages of the present disclosure are apparent from the following detailed description taken in conjunction with the accompanying drawings in which:

FIG. 1 is a cross-sectional view of a gas turbine engine;

FIG. 2 is a schematic illustration of a starting system for a gas turbine engine in accordance with an embodiment of the disclosure;

FIG. 3 is a schematic illustration of a starting system for a gas turbine engine in accordance with another embodiment of the disclosure;



3

FIG. 4 is a block diagram of a system for bowed rotor start mitigation in accordance with an embodiment of the disclosure;

FIG. 5 is a flow chart illustrating a method of bowed rotor start mitigation of a gas turbine engine in accordance with an embodiment of the disclosure;

FIG. 6 is a graph illustrating a bowed rotor risk score with respect to time in accordance with an embodiment of the disclosure;

FIG. 7 is a graph illustrating a normal or cooled engine start versus a modified engine start in accordance with an embodiment of the disclosure;

FIG. 8 is a graph illustrating examples of various vibration level profiles of an engine in accordance with an embodiment of the disclosure;

FIG. 9 is a schematic illustration of a high spool gas path with a straddle-mounted spool in accordance with an embodiment of the disclosure;

FIG. 10 is a schematic illustration of a high spool gas path with an overhung spool in accordance with an embodiment of the disclosure;

FIG. 11 is a graph illustrating commanded starter valve opening with respect to time in accordance with an embodiment of the disclosure; and

FIG. 12 is a graph illustrating a target rotor speed profile of a dry motoring profile and an actual rotor speed versus time in accordance with an embodiment of the disclosure.

#### DETAILED DESCRIPTION

Various embodiments of the present disclosure are related to a bowed rotor start mitigation system in a gas turbine engine. Embodiments can include a mission risk factor model used to estimate heat stored in an engine core at shutdown and identify a risk of a bowed rotor in the gas turbine engine based on one or more aircraft parameters. Information from the mission risk factor model can be used by a bowed rotor start risk model to calculate a bowed rotor risk parameter. As used herein the term "model" may be referred to in one non-limiting manner as a process for representing real world values, measurements or conditions through the use of a computer program or algorithm. The bowed rotor risk parameter may be used to take a control action to mitigate the risk of starting the gas turbine engine with a bowed rotor. The control action can include performing dry motoring as further described herein.

During dry motoring, a starter valve can be actively adjusted to deliver air pressure from an air supply to an engine starting system that controls starting rotor speed. Dry motoring may be performed by running an engine starting system at a lower speed with a longer duration than typically used for engine starting while dynamically adjusting the starter valve to maintain the rotor speed and/or follow a dry motoring profile. Some embodiments increase the rotor speed of the starting spool to approach a critical rotor speed gradually and as thermal distortion is decreased they then accelerate beyond the critical rotor speed to complete the engine starting process. The critical rotor speed refers to a major resonance speed where, if the temperatures are unhomogenized, the combination of a bowed rotor and similarly bowed casing and the resonance would lead to high amplitude oscillation in the rotor and high rubbing of blade tips on one side of the rotor, especially in the high pressure compressor if the rotor is straddle-mounted.

In some embodiments, a targeted rotor speed profile of the dry motoring profile can be adjusted as dry motoring is performed. As one example, if excessive vibration is

4

detected as the rotor speed rises and approaches but remains well below the critical rotor speed, then the rate of rotor speed increases scheduled in the dry motoring profile can be reduced (i.e., a shallower slope) to extend the dry motoring time. Similarly, if vibration levels are observed below an expected minimum vibration level as the rotor speed increases, the dry motoring profile can be adjusted to a higher rate of rotor speed increases to reduce the dry motoring time.

A full authority digital engine control (FADEC) system or other system may send a message to the cockpit to extend time at idle to cool down the rotor prior to shut down. If the engine is in a ground test or in a test stand, a message can be sent to the test stand or cockpit based on the control-calculated risk of a bowed rotor. A test stand crew can be alerted regarding a requirement to bring the starting spool of the engine to a speed below the known resonance speed of the rotor in order to homogenize the temperature of the rotor and the casings about the rotor which also are distorted by temperature non-uniformity.

Monitoring of vibration signatures during the engine starting sequence can also or separately be used to assess the risk that a bowed rotor start has occurred due to some system malfunction and then direct maintenance, for instance, in the case of suspected outer air seal rub especially in the high compressor. Vibration data for the engine can also be monitored after bowed rotor mitigation is performed during an engine start sequence to confirm success of bowed rotor mitigation. If bowed rotor mitigation is unsuccessful or determined to be incomplete by the FADEC, resulting metrics (e.g., time, date, global positioning satellite (GPS) coordinates, vibration level vs. time, etc.) of the attempted bowed rotor mitigation can be recorded and/or transmitted to direct maintenance.

According to various embodiments, there are a number of options available to mitigate a bowed rotor start depending on a present operating state of the gas turbine engine, instrumentation, and monitoring systems implemented. For example, a control-calculated risk of a bowed rotor can be computed as a bowed rotor risk parameter as further described herein and used to trigger a cockpit message or test stand message to extend a time period to run at idle power prior to engine shutdown as a pre-shutdown mitigation. Alternatively, the bowed rotor risk parameter can trigger a request message or automated initiation of a dry motoring sequence prior to engine start. During a dry motoring sequence, a starter air pressure valve can be modulated to limit high rotor speed below high spool resonance speed and prevent rub during dry motoring operation. The bowed rotor risk parameter can also be used to limit dry motoring duration to reduce the impact on air starter turbine life. The monitoring of vibration signatures during the entire engine starting sequence can also or separately be used to assess the risk of a bowed rotor start and direct maintenance, for instance, in the case of suspected outer air seal rub especially in the high compressor.

Rather than using sensed parameters of an engine system, embodiments use parameters at the aircraft level, e.g., as received on an aircraft communication bus, to derive parameters at the engine level, such as engine core temperature. For example, a profile of a throttle lever angle (TLA) parameter history can indicate a history of fuel flow requested over a period of time which may be used to infer an engine core temperature. By determining an amount of elapsed time from the last received valid set of aircraft



## 5

parameters in combination with a known engine state, e.g., engine shutdown, a minimum dry motoring time can be calculated.

Referring now to FIG. 1, a schematic illustration of a gas turbine engine 10 is provided. The gas turbine engine 10 has among other components a fan through which ambient air is propelled into the engine housing, a compressor for pressurizing the air received from the fan and a combustor wherein the compressed air is mixed with fuel and ignited for generating combustion gases. The gas turbine engine 10 further comprises a turbine section for extracting energy from the combustion gases. Fuel is injected into the combustor of the gas turbine engine 10 for mixing with the compressed air from the compressor and ignition of the resultant mixture. The fan, compressor, combustor, and turbine are typically all concentric about a central longitudinal axis of the gas turbine engine 10. Thus, thermal deflection of the components of the gas turbine engine 10 may create the aforementioned bowing or “bowed rotor” condition along the common central longitudinal axis of the gas turbine engine 10 and thus it is desirable to clear or remove the bowed condition prior to the starting or restarting of the gas turbine engine 10.

FIG. 1 schematically illustrates a gas turbine engine 10 that can be used to power an aircraft, for example. The gas turbine engine 10 is disclosed herein as a multi-spool turbofan that generally incorporates a fan section 22, a compressor section 24, a combustor section 26 and a turbine section 28. The fan section 22 drives air along a bypass flowpath while the compressor section 24 drives air along a core flowpath for compression and communication into the combustor section 26 then expansion through the turbine section 28. Although depicted as a turbofan gas turbine engine in the disclosed non-limiting embodiment with two turbines and is sometimes referred to as a two spool engine, it should be understood that the concepts described herein are not limited to use with turbofans as the teachings may be applied to other types of turbine engines including three-spool architectures. In both of these architectures the starting spool is that spool that is located around the combustor, meaning the compressor part of the starting spool is flowing directly into the combustor and the combustor flows directly into the turbine section.

The engine 10 generally includes a low speed spool 30 and a high speed spool 32 mounted for rotation about an engine central longitudinal axis A relative to an engine static structure 36 via several bearing systems 38. It should be understood that various bearing systems 38 at various locations may alternatively or additionally be provided.

The low speed spool 30 generally includes an inner shaft 40 that interconnects a fan 42, a low pressure compressor 44 and a low pressure turbine 46. The inner shaft 40 is connected to the fan 42 through a geared architecture 48 to drive the fan 42 at a lower speed than the low speed spool 30 in the example of FIG. 1. The high speed spool 32 includes an outer shaft 50 that interconnects a high pressure compressor 52 and high pressure turbine 54. A combustor 56 is arranged between the high pressure compressor 52 and the high pressure turbine 54. A mid-turbine frame 57 of the engine static structure 36 is arranged generally between the high pressure turbine 54 and the low pressure turbine 46. The mid-turbine frame 57 further supports bearing systems 38 in the turbine section 28. The inner shaft 40 and the outer shaft 50 are concentric and rotate via bearing systems 38 about the engine central longitudinal axis A which is collinear with their longitudinal axes.

## 6

The core airflow is compressed by the low pressure compressor 44 then the high pressure compressor 52, mixed and burned with fuel in the combustor 56, then expanded over the high pressure turbine 54 and low pressure turbine 46. The mid-turbine frame 57 includes airfoils 59 which are in the core airflow path. The turbines 46, 54 rotationally drive the respective low speed spool 30 and high speed spool 32 in response to the expansion.

A number of stations for temperature and pressure are defined with respect to the gas turbine engine 10 according to conventional nomenclature. Station 2 is at an inlet of low pressure compressor 44 having a temperature T2 and a pressure P2. Station 2.5 is at an exit of the low pressure compressor 44 having a temperature T2.5 and a pressure P2.5. Station 3 is at an inlet of the combustor 56 having a temperature T3 and a pressure P3. Station 4 is at an exit of the combustor 56 having a temperature T4 and a pressure P4. Station 4.5 is at an exit of the high pressure turbine 54 having a temperature T4.5 and a pressure P4.5. Station 5 is at an exit of the low pressure turbine 46 having a temperature T5 and a pressure P5. Embodiments use aircraft-derived parameters rather than measured parameters at the stations depicted in FIG. 1 for bowed rotor mitigation.

Although FIG. 1 depicts one example configuration, it will be understood that embodiments as described herein can cover a wide range of configurations. For example, embodiments may be implemented in a configuration that is described as a “straddle-mounted” spool 32A of FIG. 9. This configuration places two bearing compartments 37A and 39A (which may include a ball bearing and a roller bearing respectively), outside of the plane of most of the compressor disks of high pressure compressor 52A and at outside at least one of the turbine disks of high pressure turbine 54A. In contrast with a straddle-mounted spool arrangement, other embodiments may be implemented using an over-hung mounted spool 32B as depicted in FIG. 10. In over-hung mounted spool 32B, a bearing compartment 37B is located forward of the first turbine disk of high pressure turbine 54B such that the high pressure turbine 54B is overhung, and it is physically located aft of its main supporting structure. The use of straddle-mounted spools has advantages and disadvantages in the design of a gas turbine, but one characteristic of the straddle-mounted design is that the span between the bearing compartments 37A and 39A is long, making the amplitude of the high spot of a bowed rotor greater and the resonance speed that cannot be transited prior to temperature homogenization is lower. For any thrust rating, the straddle mounted arrangement, such as straddle-mounted spool 32A, gives  $L_{\text{support}}/D_{\text{hpt}}$  values that are higher, and the over-hung mounted arrangement, such as overhung spool 32B, can be as much as 60% of the straddle-mounted  $L_{\text{support}}/D_{\text{hpt}}$ .  $L_{\text{support}}$  is the distance between bearings (e.g., between bearing compartments 37A and 39A or between bearing compartments 37B and 39B), and  $D_{\text{hpt}}$  is the diameter of the last blade of the high pressure turbine (e.g., high pressure turbine 54A or high pressure turbine 54B). As one example, a straddle-mounted engine starting spool, such as straddle-mounted spool 32A, with a roller bearing at bearing compartment 39A located aft of the high pressure turbine 54A may be more vulnerable to bowed rotor problems since the  $L_{\text{support}}/D_{\text{hpt}}$  ranges from 1.9 to 5.6. FIGS. 9 and 10 also illustrate a starter 120 interfacing via a tower shaft 55 with the straddle-mounted spool 32A proximate high compressor 52A and interfacing via tower shaft 55 with the overhung mounted spool 32B proximate high compressor 52B as part of a starting system.



Turning now to FIG. 2, a schematic of a starting system **100** for the gas turbine engine **10** of FIG. 1 is depicted according to an embodiment. The starting system **100** is also referred to generally as a gas turbine engine system. In the example of FIG. 2, the starting system **100** includes a controller **102** which may be an electronic engine control, such as a dual-channel FADEC, and/or engine health monitoring unit. In an embodiment, the controller **102** may include memory to store instructions that are executed by one or more processors. The executable instructions may be stored or organized in any manner and at any level of abstraction, such as in connection with a controlling and/or monitoring operation of the engine **10** of FIG. 1. The one or more processors can be any type of central processing unit (CPU), including a general purpose processor, a digital signal processor (DSP), a microcontroller, an application specific integrated circuit (ASIC), a field programmable gate array (FPGA), or the like. Also, in embodiments, the memory may include random access memory (RAM), read only memory (ROM), or other electronic, optical, magnetic, or any other computer readable medium onto which is stored data and control algorithms in a non-transitory form.

The starting system **100** can also include a data storage unit (DSU) **104** that retains data between shutdowns of the gas turbine engine **10** of FIG. 1. The DSU **104** includes non-volatile memory and retains data between cycling of power to the controller **102** and DSU **104**. An aircraft communication bus **106** can include an aircraft-level and/or test stand communication bus to interface with aircraft controls, e.g., a cockpit, various onboard computer systems, and/or a test stand. Based on detecting a bowed rotor start risk, the controller **102** can send a request for extended idle operation on the aircraft communication bus **106** prior to engine shutdown. Alternatively, the controller **102** can receive a request to initiate bowed rotor mitigation on the aircraft communication bus **106**.

A motoring system **108** is operable to drive rotation of a starting spool (e.g., high speed spool **32**) of the gas turbine engine **10** of FIG. 1. Either or both channels of controller **102** can alternate on and off commands to an electromechanical device **110** coupled to a discrete starter valve **116A** to achieve a partially open position of the discrete starter valve **116A** to control a flow from a starter air supply **114** (also referred to as air supply **114**) through a transfer duct **118** to an air turbine starter **120** (also referred to as starter **120** or pneumatic starter motor **120**) to drive rotation of a starting spool of the gas turbine engine **10** below an engine idle speed. The air supply **114** (also referred to as starter air supply **114**) can be provided by any known source of compressed air, such as an auxiliary power unit or ground cart.

The controller **102** can monitor a speed sensor, such as speed pickup **122** that may sense the speed of the engine rotor through its connection to a gearbox **124** which is in turn connected to the high speed spool **32** via tower shaft **55** (e.g., rotational speed of high speed spool **32**) or any other such sensor for detecting or determining the speed of the gas turbine engine **10** of FIG. 1. The starter **120** may be coupled to the gearbox **124** of the gas turbine engine **10** of FIG. 1 directly or through a transmission such as a clutch system (not depicted). The controller **102** can establish a control loop with respect to rotor speed to adjust positioning of the discrete starter valve **116A**.

The discrete starter valve **116A** is an embodiment of a starter valve that is designed as an on/off valve which is typically commanded to either fully opened or fully closed. However, there is a time lag to achieve the fully open

position and the fully closed position. By selectively alternating an on-command time with an off-command time through the electromechanical device **110**, intermediate positioning states (i.e., partially opened/closed) can be achieved. The controller **102** can modulate the on and off commands (e.g., as a duty cycle using pulse width modulation) to the electromechanical device **110** to further open the discrete starter valve **116A** and increase a rotational speed of the starting spool of the gas turbine engine **10** of FIG. 1. In an embodiment, the electromechanical device **110** has a cycle time defined between an off-command to an on-command to the off-command that is at least half of a movement time for the discrete starter valve **116A** to transition from fully closed to fully open. Pneumatic lines **112A** and **112B** or a mechanical linkage (not depicted) can be used to drive the discrete starter valve **116A** between the open position and the closed position. The electromechanical device **110** can be a solenoid that positions the discrete starter valve **116A** based on intermittently supplied electric power as commanded by the controller **102**. In an alternate embodiment, the electromechanical device **110** is an electric valve controlling muscle air to adjust the position of the discrete starter valve **116A** as commanded by the controller **102**.

In the example of FIG. 2, the engine also includes a vibration monitoring system **126**. The vibration monitoring system **126** includes at least one vibration pickup **128**, e.g., an accelerometer, operable to monitor vibration of the gas turbine engine **10** of FIG. 1. Vibration signal processing **130** can be performed locally with respect to the vibration pickup **128**, within the controller **102**, or through a separate vibration processing system, which may be part of an engine health monitoring system to acquire vibration data **132**. Alternatively, the vibration monitoring system **126** can be omitted in some embodiments.

Similar to FIG. 2, FIG. 3 is a schematic illustration of a starting system **100A** for the gas turbine engine **10** of FIG. 1 in accordance with another embodiment. The starting system **100A** includes controller **102** that controls motoring system **108A**, as an alternate embodiment of the motoring system **108** of FIG. 2. Rather than using an electromechanical device **110** coupled to a discrete starter valve **116A** to achieve a partially open position of the discrete starter valve **116A** of FIG. 2, the motoring system **108A** of FIG. 3 uses a variable position starter valve **116B**. In FIG. 3, either or both channels of controller **102** can output a valve control signal **150** operable to dynamically adjust a valve angle of the variable position starter valve **116A** that selectively allows a portion of the air supply **114** to pass through the variable position starter valve **116B** and transfer duct **118** to air turbine starter **120**. The variable position starter valve **116B** is a continuous/ininitely adjustable valve that can hold a commanded valve angle, which may be expressed in terms of a percentage open/closed and/or an angular value (e.g., degrees or radians). Performance parameters of the variable position starter valve **116B** can be selected to meet dynamic response requirements of the starting system **100A**. For example, in some embodiments, the variable position starter valve **116B** has a response rate of 0% to 100% open in less than 40 seconds. In other embodiments, the variable position starter valve **116B** has a response rate of 0% to 100% open in less than 30 seconds. In further embodiments, the variable position starter valve **116B** has a response rate of 0% to 100% open in less than 20 seconds.

The controller **102** can monitor a valve angle of the variable position starter valve **116B** using valve angle feedback signals **152** provided to both channels of controller



102. As one example, in an active/standby configuration, both channels of the controller 102 can use the valve angle feedback signals 152 to track a current valve angle, while only one channel designated as an active channel outputs valve control signal 150. Upon a failure of the active channel, the standby channel of controller 102 can take over as the active channel to output valve control signal 150. In an alternate embodiment, both channels of controller 102 output all or a portion of a valve angle command simultaneously on the valve control signals 150. The controller 102 can establish an outer control loop with respect to rotor speed and an inner control loop with respect to the valve angle of the variable position starter valve 116B.

As in the example of FIG. 2, the starting system 100A of FIG. 3 also includes vibration monitoring system 126. The vibration monitoring system 126 includes at least one vibration pickup 128, e.g., an accelerometer, operable to monitor vibration of the gas turbine engine 10 of FIG. 1. Vibration signal processing 130 can be performed locally with respect to the vibration pickup 128, within the controller 102, or through a separate vibration processing system, which may be part of an engine health monitoring system to acquire vibration data 132. Alternatively, the vibration monitoring system 126 can be omitted in some embodiments.

FIG. 4 is a block diagram of a system 200 for bowed rotor start mitigation that may control the discrete starter valve 116A of FIG. 2 or the variable position starter valve 116B of FIG. 3 via control signals 210 in accordance with an embodiment. The system 200 may also be referred to as a bowed rotor start mitigation system. In the example of FIG. 3, the system 200 includes a mission risk factor model 204 which may be part of controller 102.

The mission risk factor model 204 determines at least one inferred engine operating thermal parameter, such as an engine temperature value or heat state ( $T_{core}$ ) of the gas turbine engine 10, based on at least one aircraft-based parameter 202 received on the aircraft communication bus 106. The at least one aircraft-based parameter 202 is an aircraft-level parameter which is not directly observable by engine system sensors coupled to the controller 102. As one example, the at least one aircraft-based parameter 202 can be a throttle lever angle (TLA) profile indicate of a history of fuel demand for the aircraft. By observing the at least one aircraft-based parameter 202 over a period of time, the mission risk factor model can infer an engine operating thermal parameter, such as  $T_{core}$ . For instance,  $T_{core}$  can be determined by relating flight profile information, e.g., altitude, thrust demand, time, etc., with known performance characteristics of the gas turbine engine 10 of FIG. 1 using a series of computations and/or look-up table(s) stored in memory of controller 102. The heat state of the engine 10 during use or  $T_{core}$  is inferred by the mission risk factor model 204 as the engine 10 is being run and valid instances of at least one aircraft-based parameter 202 are received on the aircraft communication bus 106. The mission risk factor model 204 can infer  $T_{core}$  absent sensed values at the engine level.

At engine shutdown, the current or most recently determined heat state of the engine or  $T_{core}$  shutdown of the engine 10 is recorded into DSU 104, and the time of the engine shutdown  $t_{shutdown}$  is recorded into the DSU 104. Time values and other parameters may be received on aircraft communication bus 106.

During an engine start sequence or restart sequence, a bowed rotor start risk model 206 of the controller 102 is provided with the data stored in the DSU 104, namely  $T_{core\ shutdown}$  and the time of the engine shutdown

$t_{shutdown}$ . In addition, the bowed rotor start risk model 206 is also provided with the time of engine start  $t_{start}$ . Although the mission risk factor model 204 and the bowed rotor start risk model 206 are separately depicted, it will be understood that the mission risk factor model 204 and the bowed rotor start risk model 206 may be combined as a single model.

The bowed rotor start risk model 206 maps core temperature model data inferred from the at least one aircraft-based parameter 202 with time data to establish a motoring time  $t_{motoring}$  as an estimated period of motoring to mitigate a bowed rotor of the gas turbine engine 10. The motoring time  $t_{motoring}$  is indicative of a bowed rotor risk parameter computed by the bowed rotor start risk model 206. The bowed rotor risk parameter may be quantified according to a profile curve 402 selected from a family of curves 404 that align with observed aircraft conditions, such as a longer duration of a higher TLA value, which increases turbine bore temperature and the resulting bowed rotor risk as depicted in the example graph 400 of FIG. 6. For instance, a higher risk of a bowed rotor may result in a longer duration of dry motoring to reduce a temperature gradient prior to starting the gas turbine engine 10 of FIG. 1. As will be discussed herein and in one embodiment, an engine start sequence may automatically include a modified start sequence; however, the duration of the modified start sequence prior to a normal start sequence will vary based upon the time period  $t_{motoring}$  that is calculated by the bowed rotor start risk model 206. The motoring time  $t_{motoring}$  for predetermined target speed  $N_{target}$  of the engine 10 can be calculated as a function of  $T_{core\ shutdown}$ ,  $t_{shutdown}$ , and  $t_{start}$  (e.g.,  $f(T_{core\ shutdown}, t_{shutdown}, \text{ and } t_{start})$ ), while a target speed  $N_{target}$  is a predetermined speed that can be fixed or vary within a predetermined speed range of  $N_{targetMin}$  to  $N_{targetMax}$ . In other words, the target speed  $N_{target}$  can be the same regardless of the calculated time period  $t_{motoring}$  or may vary within the predetermined speed range of  $N_{targetMin}$  to  $N_{targetMax}$ . The target speed  $N_{target}$  may also be referred to as a dry motoring mode speed.

Based upon these values ( $T_{core\ shutdown}$ ,  $t_{shutdown}$ , and  $t_{start}$ ) the motoring time  $t_{motoring}$  at a predetermined target speed  $N_{target}$  for the modified start sequence of the engine 10 is determined by the bowed rotor start risk model 206. Based upon the calculated time period  $t_{motoring}$  which is calculated as a time to run the engine 10 at a predetermined target speed  $N_{target}$  in order to clear a "bowed condition". In accordance with an embodiment of the disclosure, the controller 102 can run through a modified start sequence upon a start command given to the engine 10 by an operator of the engine 10 such as a pilot of an airplane the engine is used with. It being understood that the motoring time  $t_{motoring}$  of the modified start sequence may be in a range of 0 seconds to minutes, which, of course, depends on the values of  $T_{core\ shutdown}$ ,  $t_{shutdown}$ , and  $t_{start}$ .

In an alternate embodiment, the modified start sequence may only be run when the bowed rotor start risk model 206 has determined that the motoring time  $t_{motoring}$  is greater than zero seconds upon receipt of a start command given to the engine 10. In this embodiment and if the bowed rotor start risk model 206 has determined that  $t_{motoring}$  is not greater than zero seconds, a normal start sequence will be initiated upon receipt of a start command to the engine 10.

Accordingly and during an engine command start, the bowed rotor start risk model 206 of the system 200 is automatically referenced wherein the bowed rotor start risk model 206 correlates the elapsed time since the last engine shutdown time and the shutdown heat state of the engine 10 as well as the current start time  $t_{start}$  in order to determine the



duration of the modified start sequence wherein motoring of the engine **10** at a reduced speed  $N_{target}$  without fuel and ignition is required. As used herein, motoring of the engine **10** in a modified start sequence refers to the turning of a starting spool by the starter **120** at a reduced speed  $N_{target}$  without introduction of fuel and an ignition source in order to cool the engine **10** to a point wherein a normal start sequence can be implemented without starting the engine **10** in a bowed rotor state. In other words, cool or ambient air is drawn into the engine **10** while motoring the engine **10** at a reduced speed in order to clear the “bowed rotor” condition, which is referred to as a dry motoring mode.

The bowed rotor start risk model **206** can output the motoring time  $t_{motoring}$  to a motoring controller **208**. The motoring controller **208** uses a dynamic control calculation in order to determine a required valve position of the starter valve **116A**, **116B** used to supply an air supply or starter air supply **114** to the engine **10** in order to limit the motoring speed of the engine **10** to the target speed  $N_{target}$  due to the position of the starter valve **116A**, **116B**. The required valve position of the starter valve **116A**, **116B** can be determined based upon an air supply pressure as well as other factors including but not limited to ambient air temperature of the aircraft, parasitic drag on the engine **10** from a variety of engine driven components such as electric generators and hydraulic pumps, and other variables such that the motoring controller **208** closes the loop for an engine motoring speed target  $N_{target}$  for the required amount of time based on the output of the bowed rotor start risk model **206**. In one embodiment, the dynamic control of the valve position (e.g., open state of the valve (e.g., fully open,  $\frac{1}{2}$  open,  $\frac{1}{4}$  open, etc.) in order to limit the motoring speed of the engine **10**) is controlled via duty cycle control (on/off timing using pulse width modulation) of electromechanical device **110** for discrete starter valve **116A**.

When the variable position starter valve **116B** of FIG. **3** is used, a valve angle **207** can be provided to motoring control **208** based on the valve angle feedback **112** of FIG. **3**. A rotor speed  $N_2$  (i.e., speed of high speed spool **32**) can be provided to the motoring controller **208** and a mitigation monitor **214**, where motoring controller **208** and a mitigation monitor **214** may be part of controller **102**. Vibration data **132** can also be provided to mitigation monitor **214**.

The risk model **206** can determine a bowed rotor risk parameter that is based on the heat stored ( $T_{core}$ ) using a mapping function or lookup table. When not implemented as a fixed rotor speed, the bowed rotor risk parameter can have an associated dry motoring profile defining a target rotor speed profile over an anticipated amount of time for the motoring controller **208** to send control signals **210**, such as valve control signals **150** for controlling variable position starter valve **116B** of FIG. **3**.

In some embodiments, an anticipated amount of dry motoring time can be used to determine a target rotor speed profile in a dry motoring profile for the currently observed conditions. As one example, one or more baseline characteristic curves for the target rotor speed profile can be defined in tables or according to functions that may be rescaled to align with the observed conditions. An example of a target rotor speed profile **1002** is depicted in graph **1000** of FIG. **12** that includes a steep initial transition portion **1004**, followed by a gradually increasing portion **1006**, and a late acceleration portion **1008** that increases rotor speed above a critical rotor speed, through a fuel-on speed and an engine idle speed. The target rotor speed profile **1002** can be rescaled with respect to time and/or select portions (e.g., portions **1004**, **1006**, **1008**) of the target rotor speed profile

**1002** can be individually or collectively rescaled (e.g., slope changes) with respect to time to extend or reduce the total motoring time. The target rotor speed profile **1002** may include all positive slope values such that the actual rotor speed **1010** is driven to essentially increase continuously while bowed rotor start mitigation is active. While the example of FIG. **12** depicts one example of the target rotor speed profile **1002** that can be defined in a dry motoring profile, it will be understood that many variations are possible in embodiments.

An example of the effects of bowed rotor mitigation are illustrated in graph **420** of FIG. **7** that depicts a normal or cooled engine start (line **432**) versus a bowed rotor or mitigated engine start (line **434**) in accordance with one non-limiting embodiment of the disclosure. At point **436**, a pilot or operator of the engine **10** sets or initiates a start command of the engine. At point **438** and after the start command is initiated, the controller **102**, based upon the risk model **206**, requires the engine to motor at a pre-determined speed ( $N_{pre-determined}$  or  $N_{target}$ ), which is less than a normal idle start speed  $N_2$  for a time ( $t_{determined}$ ). The pre-determined speed ( $N_{pre-determined}$  or  $N_{target}$ ) can be defined within a predetermined speed range  $N_{targetMin}$  to  $N_{targetMax}$  that is used regardless of the calculated time period  $t_{motoring}$  for homogenizing engine temperatures. The time period  $t_{determined}$  is based upon the output of the risk model **206**. The determined speed ( $N_{pre-determined}$  or  $N_{target}$ ) is achieved by controlling the operational position of starter valve **116A**, **116B**. Thereafter and at point **440** when the required motoring time (determined from the risk model **206**) has been achieved, such that the “bowed condition” has been cleared a normal start sequence with a normal speed  $N_2$  is initiated. Subsequently and at point **442**, the idle speed  $N_2$  has been achieved. This modified sequence is illustrated in one non-limiting manner by the dashed line **434** of the graph **420** of FIG. **7**. It is, of course, understood that ( $t_{determined}$ ) may vary depending upon the outputs of the risk model **206**, while  $N_{pre-determined}$  or  $N_{target}$  is a known value. Of course, in alternative embodiments, the risk model **206** may be configured to provide the speed of the engine **10** during a modified start sequence. Still further and as mentioned above, the starter valve may be dynamically varied based upon the outputs of the risk model **206** as well as the pressure of the air supply **114** in order to limit the motoring speed of the engine **10** to that of  $N_{pre-determined}$  or  $N_{target}$  during the clearing of a bowed rotor condition. Line **432** illustrates a normal start sequence wherein the time  $t_{determined}$  is zero for a modified start as determined by the risk model **206**.

The example of FIG. **11** illustrates how a valve angle command **902** can be adjusted between 0 to 100% of a commanded starter valve opening to generate the actual rotor speed **1010** of FIG. **12**. As the actual rotor speed **1010** tracks to the steep initial transition portion **1004** of the target rotor speed profile **1002**, the valve angle command **902** transitions through points “a” and “b” to fully open the variable position starter valve **116B**. As the slope of the target rotor speed profile **1002** is reduced in the gradually increasing portion **1006**, the valve angle command **902** is reduced between points “b” and “c” to prevent the actual rotor speed **1010** from overshooting the target rotor speed profile **1002**. In some embodiments, decisions to increase or decrease the commanded starter valve opening is based on monitoring a rate of change of the actual rotor speed **1010** and projecting whether the actual rotor speed **1010** will align with the target rotor speed profile **1002** at a future time. If it is determined that the actual rotor speed **1010** will not align



with the target rotor speed profile **1002** at a future time, then the valve angle of the variable position starter valve **116B** is adjusted (e.g., increase or decrease the valve angle command **902**) at a corresponding time. In the example of FIGS. **11** and **12**, the valve angle command **902** oscillates with a gradually reduced amplitude between points “c”, “d”, and “e” as the actual rotor speed **1010** tracks to the target rotor speed profile **1002** through the gradually increasing portion **1006**. As dry motoring continues, the overall homogenization of the engine **10** increases, which allows the actual rotor speed **1010** to safely approach the critical rotor speed without risking damage. The valve angle command transitions from point “e” to point “f” and beyond to further increase the actual rotor speed **1010** in the late acceleration portion **1008** above the critical rotor speed, through a fuel-on speed and an engine idle speed. By continuously increasing the actual rotor speed **1010** during dry motoring, the bowed rotor condition can be reduced faster than holding a constant slower speed.

As one example of an aircraft that includes systems as described herein, mission risk factor model **204** may run on controller **102** of the aircraft to track heat stored ( $T_{core}$ ) in the turbine at the time of engine shutdown. Modeling of potential heat stored in the system may be performed as a turbine disk metal temperature model in the mission risk factor model **204**. When the aircraft lands, engines typically operate at idle for a cool down period of time, e.g., while taxiing to a final destination. When an engine shutdown is detected, model state data can be logged by the DSU **104** prior to depowering. When the controller **102** powers on at a later time and model state data can be retrieved from the DSU **104**, and the bowed rotor start risk model **206** can be updated to account for the elapsed time. When an engine start is requested, a bowed rotor risk can be assessed with respect to the bowed rotor start risk model **206**. Extended dry motoring can be performed during an engine start process until the bow risk has sufficiently diminished. If a safety condition is detected by the controller **102**, for instance, a notification that maintenance will be performed, an abort signal **220** can be triggered to halt dry motoring.

In reference to FIGS. **4** and **12**, the mitigation monitor **214** of FIG. **4** can operate in response to receiving a complete indicator **212** to run a verification of the bowed rotor mitigation. The mitigation monitor **214** can provide mitigation results **216** to the motoring controller **208** and may provide result metrics **218** to other systems, such a maintenance request or indicator. Peak vibrations can be checked by the mitigation monitor **214** during the start processes to confirm that bowed rotor mitigation successfully removed the bowed rotor condition. The mitigation monitor **214** may also run while dry motoring is active to determine whether adjustments to the dry motoring profile are needed. For example, if a greater amount of vibration is detected than was expected, the mitigation monitor **214** can request that the motoring controller **208** reduce a slope of the target rotor speed profile **1002** of FIG. **12** to extend the dry motoring time before driving the actual rotor speed **1010** of FIG. **12** up to the critical rotor speed. Similarly, if the magnitude of vibration observed by the mitigation monitor **214** is less than expected, the mitigation monitor **214** can request that the motoring controller **208** increase a slope of the target rotor speed profile **1002** of FIG. **12** to reduce the dry motoring time before driving the actual rotor speed **1010** of FIG. **12** up to the critical rotor speed.

FIG. **5** is a flow chart illustrating a method **300** of bowed rotor start mitigation of a gas turbine engine in accordance with an embodiment. The method **300** of FIG. **5** is described

in reference to FIGS. **1-12** and may be performed with an alternate order and include additional steps. At block **302**, the controller **102** receives at least one aircraft-based parameter **202** on aircraft communication bus **106**. At block **304**, the controller **102** determines at least one inferred engine operating thermal parameter (e.g.,  $T_{core}$ ) from the at least one aircraft-based parameter **202** (e.g., TLA). The at least one inferred engine operating thermal parameter can be selected from data describing a history of the aircraft before an engine shutdown.

At block **306**, the controller **102** controls the motoring system **108**, **108A** to drive rotation of a starting spool of the gas turbine engine **10** below an engine idle speed based on determining that the at least one inferred engine operating thermal parameter is within a preselected threshold. The preselected threshold may be a value or range where a greater risk of a bowed rotor condition exists. The motoring system **108**, **108A** can be controlled as described above depending on the system implementation. The controller **102** may transmit a notification on the aircraft communication bus **106** that the gas turbine engine **10** is being conditioned for starting to inform aircraft crew and/or a test stand operator. The time since the engine shutdown  $t_{shutdown}$  can be used to modify a time of rotation for dry motoring. If time data is unavailable from the DSU **104**, dry motoring can be performed for a maximum expected time assuming worst case conditions.

If the controller **102** detects a safety condition (which may include data received on the aircraft communication bus **106**) while dry motoring is active, the controller **102** can trigger abort signal **220** to abort rotation of the starting spool. A braking torque may be applied to the starting spool to abort rotation of the starting spool based on the abort signal **220**. The controller **102** can also monitor for rotary motion of the shaft using a rotation sensor, such as speed pickup **122** or an alternate sensor that detects rotor speed  $N_2$ . The controller **102** can trigger removal of power from the motoring system **108**, **108A** based on detecting rotary motion of the starting spool above a target speed (e.g., target speed  $N_{target}$ ). For example, dry motoring may not be needed if wind or other forces drive rotation of the high speed spool **32**.

In embodiments, the risk model **206** can be used to determine a motoring time period  $t_{motoring}$  for a start sequence of the gas turbine engine **10**, where the risk model **206** uses the recorded time of the engine shutdown and the stored heat state of the gas turbine engine **10** at shut down to determine the motoring time period  $t_{motoring}$ . The gas turbine engine **10** is motored at a predetermined speed range of  $N_{targetMin}$  to  $N_{targetMax}$  during the motoring time period, which is less than a normal idle start speed  $N_2$ . The controller **102** can dynamically vary a position of starter valve **116A**, **116B** during the motoring time period in order to motor the gas turbine engine **10** at the predetermined speed range of  $N_{targetMin}$  to  $N_{targetMax}$ . The predetermined speed range of  $N_{targetMin}$  to  $N_{targetMax}$  may be tightly controlled to a substantially constant rotor speed or cover a wider operating range according to a dry motoring profile.

As one example with respect to FIGS. **3** and **12**, the variable position starter valve **116B** can be initially set to a valve angle of greater than 50% open when bowed rotor start mitigation is active. The controller **102** can monitor a rate of change of the actual rotor speed **1010**, project whether the actual rotor speed **1010** will align with the target rotor speed profile **1002** at a future time based on the rate of change of the actual rotor speed **1010**, and adjust a valve angle of the variable position starter valve **116B** based on determining



that the actual rotor speed **1010** will not align with the target rotor speed profile **1002** at a future time.

Further dynamic updates at runtime can include adjusting a slope of the target rotor speed profile **1002** in the dry motoring profile while the bowed rotor start mitigation is active based on determining that a vibration level of the gas turbine engine **10** is outside of an expected range. Adjusting the slope of the target rotor speed profile **1002** can include maintaining a positive slope. Vibration levels may also or alternatively be used to check/confirm successful completion of bowed rotor start mitigation prior to starting the gas turbine engine **10**. For instance, based on determining that the bowed rotor start mitigation is complete, a vibration level of the gas turbine engine **10** can be monitored while sweeping through a range of rotor speeds including the critical rotor speed.

In further reference to FIG. **4**, the mitigation monitor **214** of FIG. **4** may receive a complete indicator **212** from the motoring controller **208** when the motoring controller **208** has completed dry motoring, for instance, if the motoring time has elapsed. If the mitigation monitor **214** determines that the bowed rotor condition still exists based on vibration data **132** collected, the motoring controller **208** may restart dry motoring, or a maintenance request or indicator can be triggered along with providing result metrics **218** for further analysis. Metrics of attempted bowed rotor mitigation can be recorded in the DSU **104** based on determining that the attempted bowed rotor mitigation was unsuccessful or incomplete.

Referring now to FIG. **8**, a graph **500** illustrating examples of various vibration level profiles **502** of an engine, such as gas turbine engine **10** of FIG. **1** is depicted. The vibration level profiles **502** represent a variety of possible vibration levels observed before and/or after performing bowed rotor mitigation. Critical rotor speed **510** is the speed at which a vibration peak is expected due to amplification effects of a bowed rotor condition along with other contributions to vibration level generally. A peak vibration **504** at critical rotor speed **510** may be used to trigger different events. For example, if the peak vibration **504** at critical rotor speed **510** is below a maintenance action threshold **506**, then no further actions may be needed. If the peak vibration **504** at critical rotor speed **510** is above a damage risk threshold **508**, then an urgent maintenance action may be requested such as an engine check. If the peak vibration **504** at critical rotor speed **510** is between the maintenance action threshold **506** and the damage risk threshold **508**, then further bowed rotor mitigation actions may be requested, such as extending/restarting dry motoring. In one embodiment, a maintenance request is triggered based on the actual vibration level exceeding maintenance action threshold **506** after completing an attempt of bowed rotor mitigation.

The lowest rotor vibration vs. speed in FIG. **8** (vibration profile **502D**) is for a fully homogenized rotor, where mitigation is not necessary (engine parked all night long, for example). The next higher curve shows a mildly bowed rotor and so on. The maintenance action threshold **506** is a threshold for setting a maintenance flag such as requiring a troubleshooting routine of one or more system elements. The damage risk threshold **508** may be a threshold to trigger a more urgent maintenance requirement up to and including an engine check. As dry motoring is performed in embodiments, the gas turbine engine **10** may shift between vibration profiles. For instance, when a bow rotor condition is present, the gas turbine engine **10** may experience vibration levels according to vibration profile **502A**, if mitigation is not

performed. As dry motoring is run, the gas turbine engine **10** may have a vibration profile that is gradually reduced from vibration profile **502A** to vibration profile **502B** and then vibration profile **502C**, for example. By checking the current vibration level at a corresponding rotor speed with respect to time, the controller **102** can determine whether adjustments are needed to extend or reduce the slope of the target rotor speed profile **1002** of FIG. **12** depending on an expected rate of bowed rotor reduction. In embodiments, a slope of the target rotor speed profile **1002** in the dry motoring profile **206** can be adjusted and maintains a positive slope while bowed rotor start mitigation is active based on determining that a vibration level of the gas turbine engine **10** is less than a targeted maximum range **512**, which may define a safe level of vibration to ensure that no risk of a maintenance action or damage will likely occur if the actual rotor speed **1010** is increased faster than previously planned.

Accordingly and as mentioned above, it is desirable to detect, prevent and/or clear a “bowed rotor” condition in a gas turbine engine that may occur after the engine has been shut down. As described herein and in one non-limiting embodiment, the controller **102** may be programmed to automatically take the necessary measures in order to provide for a modified start sequence without pilot intervention other than the initial start request. In an exemplary embodiment, the controller **102** and/or DSU **104** comprises a microprocessor, microcontroller or other equivalent processing device capable of executing commands of computer readable data or program for executing a control algorithm and/or algorithms that control the start sequence of the gas turbine engine. In order to perform the prescribed functions and desired processing, as well as the computations therefore (e.g., the execution of Fourier analysis algorithm(s), the control processes prescribed herein, and the like), the controller **102** and/or DSU **104** may include, but not be limited to, a processor(s), computer(s), memory, storage, register(s), timing, interrupt(s), communication interfaces, and input/output signal interfaces, as well as combinations comprising at least one of the foregoing. For example, the controller **102** and/or DSU **104** may include input signal filtering to enable accurate sampling and conversion or acquisitions of such signals from communications interfaces. As described above, exemplary embodiments of the disclosure can be implemented through computer-implemented processes and apparatuses for practicing those processes.

While the present disclosure has been described in detail in connection with only a limited number of embodiments, it should be readily understood that the present disclosure is not limited to such disclosed embodiments. Rather, the present disclosure can be modified to incorporate any number of variations, alterations, substitutions or equivalent arrangements not heretofore described, but which are commensurate with the spirit and scope of the present disclosure. Additionally, while various embodiments of the present disclosure have been described, it is to be understood that aspects of the present disclosure may include only some of the described embodiments. Accordingly, the present disclosure is not to be seen as limited by the foregoing description, but is only limited by the scope of the appended claims.

What is claimed is:

1. A bowed rotor start mitigation system for a gas turbine engine of an aircraft, the bowed rotor start mitigation system comprising:



17

- a motoring system; and  
 a controller coupled to the motoring system and an aircraft communication bus, wherein the controller is configured to perform:
- 5 determining at least one inferred engine operating thermal parameter based on at least one aircraft-based parameter received on the aircraft communication bus, wherein the at least one inferred engine operating thermal parameter is based on data describing a history of the aircraft before an engine shutdown; and
  - 10 controlling the motoring system to drive rotation of a starting spool of the gas turbine engine below an engine idle speed based on determining that the at least one inferred engine operating thermal parameter is within a preselected range.
  2. The bowed rotor start mitigation system as in claim 1, wherein the at least one aircraft-based parameter is indicative of a history of fuel demand for the aircraft.
  3. The bowed rotor start mitigation system as in claim 1, wherein a time since the engine shutdown is used to modify a time of rotation of the starting spool by the motoring system.
  4. The bowed rotor start mitigation system as in claim 1, wherein the controller transmits a notification on the aircraft communication bus based on the gas turbine engine being conditioned for starting.
  5. The bowed rotor start mitigation system as in claim 1, wherein the controller is configured to abort rotation by the motoring system when a safety condition is detected.
  6. The bowed rotor start mitigation system as in claim 5, wherein the motoring system is configured to apply a braking torque to the starting spool to abort rotation of the starting spool.
  7. The bowed rotor start mitigation system as in claim 1, further comprising a rotation sensor for detecting rotary motion of the starting spool, and the controller is further coupled to the rotation sensor.
  8. The bowed rotor start mitigation system as in claim 7, wherein the controller is configured to remove power from the motoring system based on detecting rotary motion of the starting spool above a target speed.
  9. The bowed rotor start mitigation system as in claim 1, wherein a vibration monitor is used to set a maintenance flag based on detecting a vibration level that exceeds a maintenance action threshold while accelerating the starting spool of the gas turbine engine.
  10. The bowed rotor start mitigation system as in claim 1, wherein the at least one inferred engine operating thermal parameter comprises an engine temperature value, and the at

18

- least one aircraft-based parameter received on the aircraft communication bus comprises a throttle lever angle profile.
11. A method of bowed rotor start mitigation for a gas turbine engine of an aircraft, the method comprising:
    - 5 determining at least one inferred engine operating thermal parameter based on at least one aircraft-based parameter received on an aircraft communication bus, wherein the at least one inferred engine operating thermal parameter is based on data describing a history of the aircraft before an engine shutdown; and
    - 10 controlling a motoring system to drive rotation of a starting spool of the gas turbine engine below an engine idle speed based on determining that the at least one inferred engine operating thermal parameter is within a preselected range.
  12. The method as in claim 11, wherein the at least one aircraft-based parameter is indicative of a history of fuel demand for the aircraft.
  13. The method as in claim 11, further comprising:
    - 20 modifying a time of rotation of the starting spool by the motoring system based on a time since the engine shutdown.
  14. The method as in claim 11, further comprising:
    - 25 transmitting a notification on the aircraft communication bus based on the gas turbine engine being conditioned for starting.
  15. The method as in claim 11, further comprising:
    - 30 aborting rotation by the motoring system when a safety condition is detected.
  16. The method as in claim 15, further comprising:
    - 35 applying a braking torque to the starting spool to abort rotation of the starting spool.
  17. The method as in claim 11, further comprising:
    - 40 detecting rotary motion of the starting spool using a rotation sensor.
  18. The method as in claim 17, further comprising:
    - 45 removing power from the motoring system based on detecting rotary motion of the starting spool above a target speed.
  19. The method as in claim 11, further comprising:
    - 50 setting a maintenance flag based on a vibration monitor detecting a vibration level that exceeds a maintenance action threshold while the starting spool of the gas turbine engine accelerates.
  20. The method as in claim 11, wherein the at least one inferred engine operating thermal parameter comprises an engine temperature value, and the at least one aircraft-based parameter received on the aircraft communication bus comprises a throttle lever angle profile.

\* \* \* \* \*